Discomfort Glare Perception from Daylight: Influence of the Socio-Environmental Context

This work was carried out at UCLouvain in the research group Architecture et Climat led by Professor Sergio Altomonte, and at EPFL in the Laboratory of Integrated Performance in Design (LIPID) led by Professor Marilyne Andersen. Clotilde Pierson was a Research Fellow of the Fonds de la Recherche Scientifique (FNRS).

Discomfort Glare Perception from Daylight: Influence of the Socio-Environmental Context

Thesis submitted in partial fullfilment of the requirements for the degree of *Docteur en Sciences de l'Ingénieur et Technologie*

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To Alex.

Abstract

"*Space and light and order. Those are the things that men need just as much as they need bread or a place to sleep.*"
[Le Corbusier]

Exposure to light, and especially to daylight, has much to offer. Regarding buildings' occupants, daylight has been shown to boost performance, improve sleep, provide a connection to the outside, increase comfort, lessen agitation, and reduce depression. Regarding buildings, daylight enhances the aesthetics of a space and improves its energy efficiency. On one condition, though: that it does not produce visual discomfort. In order to harvest the benefits of daylight, visual discomfort has to be minimized. Hence, discomfort glare from daylight should be predictable.

To date, more than twenty daylight discomfort glare models have been developed. However, none of them can consistently and accurately explain the large variation between subjects' discomfort glare perception. Improving current models predicting discomfort glare perception remains a crucial step to move towards optimal daylighting design in buildings.

In this context, it is hypothesized that the prediction of discomfort glare perception can be improved by including relevant additional factors related to the context or to the subject in the models. The main research question that this study aims to answer is to determine whether one of these factors, namely the socio-environmental context of the subject, influences discomfort glare perception from daylight in office buildings. The socio-environmental context is de-

fined here as the climate and habitat, including indoors and outdoors, to which a subject has been acclimatized, her/his behavior toward these elements, and her/his expectations about them. Two additional research questions aim at investigating other potentially influencing factors and potential experimental biases in order to guide further research in the field.

For this purpose, a field study was conducted in real office buildings located in four socio-environmental contexts, i.e., Chile, Belgium, Japan, and Switzerland. Discomfort glare perception evaluations, each consisting of a subjective assessment of discomfort glare from daylight and the measurement of the visual stimulus, were collected at the office desk of the 401 subjects who took part in the study. The raw data was processed to derive useful information, and cleansed according to specific rules to ensure data quality.

Different statistical analyses were conducted on the processed and cleansed data to answer the main research question. No statistically significant differences in the sensitivity to discomfort glare from daylight could be observed between the subjects acclimatized to the Chilean, Belgian, Japanese, and Swiss contexts. The results show therefore no evidence of an influence of the socio-environmental context of a subject on discomfort glare perception from daylight in office buildings.

Furthermore, the influence of several other factors on discomfort glare perception from daylight in office buildings was tested and the data was further analyzed regarding potential experimental biases in order to answer the two additional research questions.

A statistically significant effect was found for three factors, namely the self-assessed glare sensitivity, the attractiveness of the view through the window, and the indoor air temperature. From this result, it can be hypothesized that these factors could influence discomfort glare perception. Moreover, further analyses suggest that two experimental biases, namely the glare rating scales and the study type, could be influencing the results of studies on discomfort glare perception. However, since the study was not specifically designed to answer these two additional research questions, and in

view of its limitations, no conclusion can be drawn on these last observations. They can, however, be used to guide the development of future studies.

In conclusion, this research provides no evidence that discomfort glare from daylight is perceived differently in different socio-environmental contexts. Research efforts in discomfort glare perception from daylight should therefore aim at improving prediction models by looking at other potential factors, such as physiological and environmental ones. Finally, future studies should also aim for the validation of reliable methods to study discomfort glare, and for the development of a unified methodological framework to promote the reproducibility of studies and the comparability of results.

Keywords: daylight, discomfort glare, perception, socio-environmental context, HDR photography

Résumé

"*L'espace, la lumière et l'ordre. Ce sont les choses dont les hommes ont besoin autant qu'ils ont besoin de pain ou d'un endroit où dormir.*"
[Le Corbusier]

L'exposition à la lumière, et en particulier à la lumière du jour, a beaucoup à offrir. En ce qui concerne les occupants des bâtiments, il a été démontré que la lumière du jour accroît les performances, améliore le sommeil, assure une connexion avec l'extérieur, augmente le confort, diminue l'agitation et réduit la dépression. En ce qui concerne les bâtiments, la lumière du jour met en valeur l'esthétique d'un espace et améliore son efficacité énergétique. Cela n'est valide qu'à une condition cependant : qu'il ne produise pas d'inconfort visuel. Afin de récolter les bénéfices de la lumière du jour, l'inconfort visuel doit être minimisé. Par conséquent, l'éblouissement d'inconfort causé par la lumière du jour devrait être prévisible.

À ce jour, plus de vingt modèles d'éblouissement d'inconfort dû à la lumière du jour ont été développés. Cependant, aucun d'entre eux ne peut expliquer de manière cohérente et précise la grande variation de la perception de l'éblouissement d'inconfort d'un sujet à l'autre. L'amélioration des modèles actuels permettant de prédire la perception de l'éblouissement d'inconfort demeure une étape cruciale afin d'avancer vers une conception optimale de l'éclairage naturel dans les bâtiments.

Dans ce contexte, nous émettons l'hypothèse que la prédiction de la

perception de l'éblouissement d'inconfort peut être améliorée en incluant dans les modèles des facteurs additionnels pertinents liés au contexte ou au sujet. La principale question de recherche à laquelle cette étude cherche à répondre est de déterminer si l'un de ces facteurs, à savoir le contexte socio-environnemental du sujet, influence la perception de l'éblouissement d'inconfort par la lumière du jour dans les immeubles de bureaux. Le contexte socio-environnemental est défini ici comme le climat et l'habitat, en ce compris l'intérieur et l'extérieur, auxquels un sujet s'est acclimaté, son comportement envers ces éléments, et ses attentes à leur égard. Deux questions de recherche supplémentaires visent à étudier d'autres facteurs potentiellement influents, ainsi que d'éventuels biais expérimentaux, afin d'orienter la recherche future dans ce domaine.

À cette fin, une étude de terrain a été menée dans des immeubles de bureaux situés dans quatre contextes socio-environnementaux différents, à savoir au Chili, en Belgique, au Japon et en Suisse. Les évaluations de la perception de l'éblouissement d'inconfort, consistant chacune en une évaluation subjective de l'éblouissement d'inconfort causé par la lumière du jour et en la mesure du stimulus visuel, ont été collectées aux bureaux des 401 sujets qui ont participé à l'étude. Les données brutes ont été traitées pour en tirer les informations nécessaires et nettoyées selon des règles spécifiques pour en assurer la qualité.

Différentes analyses statistiques ont été effectuées sur les données traitées et nettoyées pour répondre à la principale question de recherche. Aucune différence statistiquement significative de la sensibilité à l'éblouissement d'inconfort dû à la lumière du jour n'a pu être observée entre les sujets acclimatés aux contextes chilien, belge, japonais et suisse. Les résultats ne montrent donc aucune preuve d'une influence du contexte socio-environnemental sur la perception de l'éblouissement d'inconfort par la lumière du jour dans les immeubles de bureaux.

De plus, l'influence de plusieurs autres facteurs sur la perception de l'éblouissement d'inconfort dû à la lumière du jour dans les immeubles de bureaux a également été testée et les données ont été

analysées plus en détails par rapport aux potentiels biais expérimentaux afin de répondre aux deux questions de recherche supplémentaires.

Un effet statistiquement significatif a été constaté pour trois facteurs, à savoir la sensibilité à l'éblouissement auto-évaluée, l'attrait de la vue à travers la fenêtre et la température de l'air intérieur. Une hypothèse peut être émise à partir de ces résultats : ces facteurs pourraient influencer la perception de l'éblouissement d'inconfort. Des analyses additionnelles suggèrent que deux biais expérimentaux, à savoir les échelles d'évaluation de l'éblouissement et le type d'étude, pourraient influencer les résultats des études sur la perception de l'éblouissement d'inconfort. Toutefois, comme cette étude n'a pas été spécifiquement conçue pour répondre à ces deux questions de recherche supplémentaires, et compte tenu de ses limitations, aucune conclusion ne peut être tirée de ces dernières observations. Les hypothèses émises peuvent toutefois servir à orienter l'élaboration d'études futures.

En conclusion, cette recherche ne fournit aucune preuve que l'éblouissement d'inconfort causé par la lumière du jour est perçu différemment dans différents contextes socio-environnementaux. Les efforts de recherche sur la perception de l'éblouissement d'inconfort dû à la lumière du jour devraient donc se concentrer sur l'amélioration des modèles de prédiction en examinant d'autres facteurs potentiels, tels que les facteurs physiologiques et environnementaux. Enfin, les études futures devraient également viser à valider des méthodes fiables pour l'étude de l'éblouissement d'inconfort, ainsi qu'à élaborer un cadre méthodologique homogénéisé pour promouvoir la reproductibilité des études et la comparabilité des résultats.

Mots-clés : lumière du jour, éblouissement d'inconfort, perception, contexte socio-environnemental, photographie HDR

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Acronyms

ANOVA ANalysis Of VAriance.

AUC Area Under the Curve.

BCD Borderline between Comfort and Discomfort.

BDI Borderline between Disturbing and Intolerable glare.

BGI British Glare Index.

BIN Borderline between Imperceptible and Noticeable glare.

BND Borderline between Noticeable and Disturbing glare.

CCT Correlated Color Temperature.

CGI CIE Glare Index.

CI Confidence Interval.

CIE Commission Internationale de l'Eclairage/International Commission on Illumination.

DGI Daylight Glare Index.

DGI$_{China}$ China Glare Index.

DGI$_{mod}$ Modified Daylight Glare Index.

DGI$_N$ New Daylight Glare Index.

DGP Daylight Glare Probability.

DGP$_{mod}$ Modified Daylight Glare Probability.

DGP$_s$ Simplified Daylight Glare Probability.

DGR Discomfort Glare Rating.

DSLR Digital Single-Lens Reflex.

E_h Horizontal Illuminance.

E_v Vertical Illuminance.

EPV Events per Predictor Variable.

FOV Field of View.

GC Glare Constant.

GHI Global Horizontal Irradiance.

GSV Glare Sensation Vote.

GVIF Generalized Variance Inflation Factor.

HDR High Dynamic Range.

ID Identifier.

IEQ Indoor Environmental Quality.

IES Illuminating Engineering Society.

ipRGC intrinsically photosensitive Retinal Ganglion Cell.

L_{mean} Mean Luminance.

LDR Low Dynamic Range.

LED Light-Emitting Diode.

LRT Likelihood Ratio Test.

MCTQ Munich Chronotype Questionnaire.

MLE Maximum-Likelihood Estimation.

MPOD Macular Pigment Optical Density.

NA Not Applicable / Not Available / No Answer.

ND Neutral Density.

OEQ Open-Ended Question.

PANAS Positive And Negative Affect Schedule.

PCA Principal Component Analysis.

PGSV Predicted Glare Sensation Vote.

$PGSV_{sat}$ Saturated Predicted Glare Sensation Vote.

ROC Receiver Operating Characteristic.

TNR True Negative Rate.

TPR True Positive Rate.
UGP Unified Glare Probability.
UGR Unified Glare Rating.
UGR$_{exp}$ Experimental Unified Glare Rating.
USA United States of America.
VCP Visual Comfort Probability.
VIF Variance Inflation Factor.

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Chapter 1

Introduction

1.1 Context

As described in [Hensen 2018], different priorities have been adopted for the development of indoor spaces in the last centuries: health was the priority in the 18th century in order to prevent the spread of diseases; comfort, and especially thermal comfort with air conditioning, became the priority in the 19th century; in the 20th century, after the oil crisis in the 1970s, the priority converted towards sustainability to save as much energy as possible. Since the beginning of the 21st century, building occupants' well-being, which includes both comfort and health, has regained the interest of people. Nowadays, the priority for the development of indoor spaces is to integrate two main challenges, namely building occupants' well-being and energy efficiency.

On the one hand, buildings alone accounted for 36% of global final energy use, and nearly 40% of energy-related carbon dioxide emissions in 2017 [IEA 2018]. From an analysis based on 73 buildings in 13 countries, the life-cycle energy requirement of office buildings was observed to fall in the range of $250 - 550$ kWh/m^2 per year, i.e., twice more than conventional residential buildings, and around 85% of this range was operational energy, namely energy required for maintaining comfort conditions and day-to-day maintenance of the buildings [Ramesh et al. 2010]. These large numbers are partly due to systems having poor energy performance and a lack of technological advances, but the human dimensions also play a significant role in affecting energy use over the building life cycle [D'Oca et al. 2018].

On the other hand, people in Western societies spend 90% of their time indoors [Klepeis et al. 2001; WHO 2014]. This percentage is larger than any other generations before. Indoor environmental factors, such as thermal factors, lighting aspects, or noise, play therefore an important role in influencing a subject's well-being [Bluyssen et al. 2011; Dreyer et al. 2018]. A recent report based on a survey conducted in 14 European countries has shown that time spent indoors can have detrimental effects on our well-being, because of poor Indoor Environmental Quality (IEQ) related, for

instance, to indoor air pollution or the lack of exposure to light [Velux 2018].

In this respect, light, and especially daylight, is a relevant factor to improve building occupants' well-being while reducing the energy consumption of the building. Studies conducted in the past few decades have shown the positive impacts that daylight can have regarding these aspects, i.e., regarding subjects' well-being [Webb 2006; Lockley 2009; Boyce et al. 2003; Boubekri 2008] and energy efficiency [Li et al. 2000; Athienitis et al. 2002; Franzetti et al. 2004; Sabry et al. 2014], as well as other aspects, such as productivity [Heschong et al. 2002a; Heschong et al. 2002b], connection to the outside [Raanaas et al. 2011; Chang et al. 2005; Kaplan 2001], or aesthetics and perception of space [Corrodi et al. 2008; Rockcastle et al. 2013; Gherri 2015].

More specifically, the relatively recent discovery of a new class of photoreceptor in the eye, the intrinsically photosensitive Retinal Ganglion Cell (ipRGC) [Hattar et al. 2002; Berson et al. 2002; Do et al. 2010], demonstrates that, besides enabling vision, light controls our circadian system, namely our internal body clock [Cajochen et al. 2014]. Light therefore regulates important physiological and behavioral rhythms, such as sleep-wake cycles, alertness and performance patterns, core body temperature, and hormone production [Ámundadóttir et al. 2013]. Studies have shown that an appropriate light exposure can reduce depression, improve sleep, lessen agitation, help adjustment to night-shift work, and boost performance [Figueiro et al. 2014; Phipps-Nelson et al. 2003; Rüger et al. 2006]. In particular, daylight has benefits over electric light in regulating circadian rhythms and maintaining occupants' well-being [Boyce et al. 2003; Boubekri 2008; Aries et al. 2015].

Furthermore, daylight is delivered at virtually no cost [Anjali 2006], and can have a significant and beneficial impact on the energy consumption of a building when integrated wisely. Several studies have demonstrated that optimizing daylight while using an electric lighting control system can lead to a significant reduction in the global energy demand for buildings [Leite Didoné et al. 2011; Cammarano

et al. 2015; Shen et al. 2012; Tsangrassoulis et al. 2017; Tzempelikos et al. 2007]. These studies show that an adequate control and integration of daylight could therefore be beneficial not only for the occupants, to support their well-being, but for the environmental and financial costs of the buildings.

Unfortunately, daylight in buildings does not only have positive sides; excessive brightness, strong contrasts, intense reflections, or direct sunlight are all causes of visual discomfort, and more specifically of glare, related to daylight [Jakubiec 2018]. When daylight produces visual discomfort, building occupants usually close their shading devices, and tend to turn on electric lighting. The most common factor that leads the occupants to close their blinds has been shown to be direct solar radiation and glare [Inoue et al. 1988; Sutter et al. 2006; Galasiu et al. 2006; Meerbeek et al. 2012]. However, when daylighting conditions have returned to a comfortable situation, occupants often forget to open the shading devices [O'Brien et al. 2013], canceling the benefits of daylight for a relatively long period.

Manual blinds have indeed been observed through field studies to undergo a very low daily rate of change, which averaged at around 15% for 426 buildings according to a literature review [Van Den Wymelenberg 2012a]. More specifically, a case study of a university building with 63 offices being monitored revealed that 36% of the subjects never adjusted their blinds over a period as long as four months [Pigg et al. 1996]. Another study conducted in summer indicated that only 5% of the motorized blinds in a building in Seoul were adjusted more than once a day [Kim et al. 2009a].

For these reasons, the manual control of shading devices strongly impacts the energy performance of a building [Bordass et al. 2001; IESNA 1999]. For instance, it was calculated that, for a south-facing office in Toronto, the manual control of blinds and electric lighting by the occupant reduced cooling energy by 7%, but increased heating energy by 17%, and lighting energy by 66% [Newsham 1994]. Another example in the Netherlands showed that the total daily average energy consumption for heating and cooling was

three times lower for occupants having automated blind control than for the manual blind users [Meerbeek et al. 2014]. Furthermore, the benefits of daylight on occupants' well-being are significantly reduced in situations where the shading devices are closed most of the time. Indeed, it was shown that daylit spaces had significant benefits in regard to circadian stimulus potential and circadian efficacy compared to non-daylit spaces [Konis 2018].

In this context, it is clear that the daylighting strategy of a building must be considered beforehand, during the building design phase, and that the control of blinds cannot be left to the occupants alone. Blind operation should therefore be partially automated, as the occupants should have the capacity to override the system since the perception of control influences satisfaction with the working environment [Veitch 2001; Meerbeek et al. 2012]. Efficiently managing daylight penetration inside buildings is essential to harvest its energy-saving and well-being benefits.

For the purpose of automatically controlling shading devices, it is not only necessary to be able to accurately predict the energy consumption related to daylight, but also the occupants' visual discomfort, and especially discomfort glare. Indeed, with the rapid development of new technologies, cutting-edge systems, which work on the basis of an algorithm and one or several light sensors, have already been implemented in buildings to control the operations of shading devices. However, these cutting-edge systems only aim at reducing the energy consumption of the buildings by maximizing daylighting while preventing overheating due to solar heat gains. The results of a field study, in which the occupants' responses to such an automated blind system were monitored over a period of 20 weeks, stressed the importance of considering the occupants and their visual discomfort in such systems [Meerbeek et al. 2012]. A majority of the building occupants (77.5%) switched off the automatic mode of the blind system permanently, and most of the occupants who did not switch off the system mentioned that it did not work properly, but that they would rather accept some discomfort than spend time on adjusting the blinds. In addition to the lack of consideration for occupants' visual comfort, the human

acceptance of such automated blind systems might also be an issue.

Today, automatic systems based on algorithms considering energy consumption along with occupants' visual discomfort are being studied and developed [Goovaerts et al. 2017; Wu et al. 2019; Kunwar et al. 2019; Xiong et al. 2019]. However, in order for these systems to perform efficiently, two challenges related to the prediction of visual discomfort remain:

1. the need to provide an accurate metric of discomfort glare perception from daylight
2. the need to find an efficient and non-invasive way of measuring lighting conditions from the building occupant's viewing point

Furthermore, improving the prediction of discomfort glare perception from daylight would make its prediction more accurate during the building design phase, and therefore provide more reliable information on which to base the daylight optimization strategy.

In order to harvest the benefits of daylight related to the building energy consumption and the occupants' well-being, this research helps tackle the first of the two challenges, by moving forward towards an accurate metric of discomfort glare perception from daylight. It is the ambition of this research to promote more sustainable buildings by improving the integration of daylight in those buildings.

1.2 Thesis Outline

The outline below provides a short explanation of the various steps undertaken to address the purpose of this research.

First, Chapter 2 (*State of the Art*) details the state of the art related to discomfort glare perception from daylight. A description of discomfort glare perception and a brief history of the metrics developed to predict discomfort glare perception from daylight are given. Furthermore, all the factors having already been studied for their potential influence on discomfort glare perception are reviewed and the current research gaps in daylight discomfort glare research are presented.

Chapter 3 (*Research Aim*) then establishes the research questions on the basis of the general research hypothesis and the state of the art.

The way in which these research questions are addressed is described in Chapter 4 (*Methodology*). First, the study design and the choices regarding the study protocol are detailed and justified. The data processing and cleansing steps are then explained. Finally, the processed and cleansed data are summarized, and some explanations regarding the statistical analyses that will be applied are given.

Before diving in the statistical analyses to answer the research questions, Chapter 5 (*Descriptive and Preparatory Analyses*) details the data collected regarding the lighting conditions and the subjects' demography through descriptive statistics. Preparatory analyses are also conducted to build the foundations for the following results chapters.

Chapter 6 (*Results: Main Research Question*) addresses the main research question of the thesis, which is to determine whether the socio-environmental context of a subject, which is defined in Subsection 2.2.3 (p.114), influences the subject's discomfort glare perception from daylight in office buildings. The data collected are analyzed, and the results are discussed.

Chapter 7 (*Results: First Additional Research Question*) addresses the first additional research question of the thesis, which is to determine whether additional factor(s), among a list of 13 preselected factors, has/ve a probable influence on the subject's discomfort glare perception from daylight in office buildings. The data collected are analyzed, and the results are discussed.

Chapter 8 (*Results: Second Additional Research Question*) addresses the second additional research question of the thesis, which is to determine whether experimental bias(es), among a list of five potential biases, has/ve a probable influence on the results of studies on discomfort glare perception. The data collected are analyzed, and the results are discussed.

Finally, Chapter 9 (*Conclusion*) summarizes the findings of this research. Implications of these findings in terms of research and practice are discussed, as well as their limitations. Four perspectives are detailed as recommendations for future studies.

Chapter 2

State of the Art

This chapter includes amended parts of a review article published in LEUKOS [Pierson et al. 2018b], of which the accepted manuscript is reproduced in Appendix H with permission of the Illuminating Engineering Society.

2.1 Discomfort Glare from Daylight

2.1.1 Visual Discomfort

Figure 2.1, which is adapted from a figure in [Kort et al. 2014], shows a schematic view of the different mechanisms governing the effects of light on humans that have been documented and studied. In this research, the focus is on the image-forming pathway, and especially on discomfort glare as a source of visual discomfort.

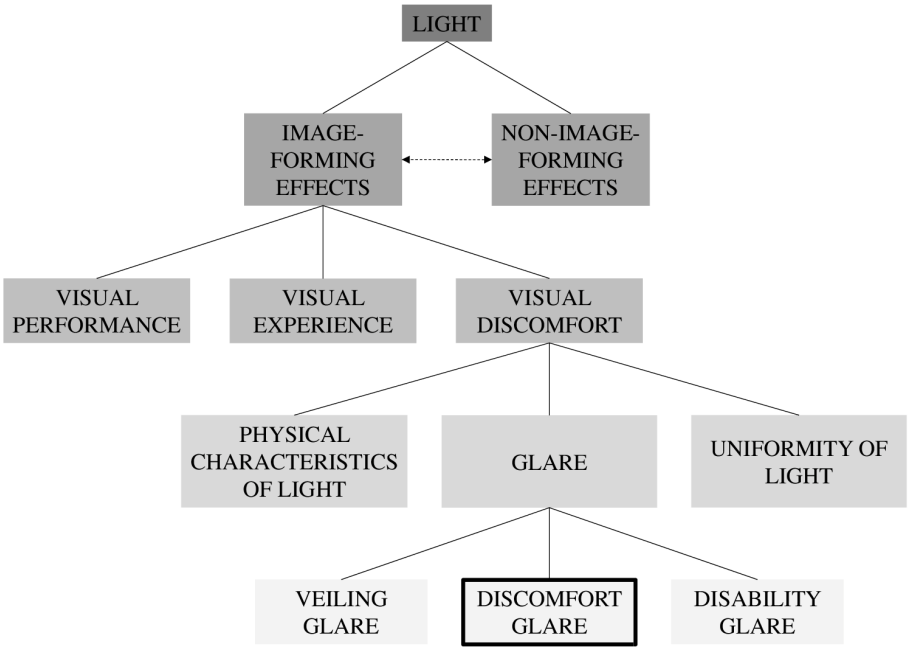


Figure 2.1: Schematic view of the mechanisms governing the effects of light on humans that have been documented and studied (figure adapted from [Kort et al. 2014])

In the image-forming pathway, visual environments can be studied in relation to three main mechanisms: visual experience, visual performance, and visual discomfort [Kort 2019]. This research focuses on visual discomfort, which refers to lighting conditions causing discomfort or pain in or around the eyes [Boyce et al. 2018].

Visual discomfort can in turn be induced by three main categories of elements related to the lighting conditions: the physical charac-

teristics of light, which includes, among others, the amount of light; glare, which includes veiling, discomfort, and disability glare; and the uniformity of light, which includes elements related to both the spatial and temporal uniformity [Boyce et al. 2018; Carlucci et al. 2015]. Therefore, shadows and flicker, which have been listed as distinct elements inducing visual discomfort [Boyce 2014], are included in the uniformity of light category in Figure 2.1. Moreover, there exists no scientific evidence of the influence of the quality of light in rendering colors on visual discomfort, although this element has already been mentioned as a fourth element inducing visual discomfort [Carlucci et al. 2015]. This element is thus not displayed on its own but could be included in the physical characteristics of light category.

From the three categories of elements inducing visual discomfort, glare is the focus of this research. Contrary to the Commission Internationale de l'Eclairage/International Commission on Illumination (CIE), which identifies only two categories [CIE 1983], Wienold defines three categories of glare: veiling glare, discomfort glare, and disability glare [Wienold 2009a]. Nowadays, most studies focus on the study of discomfort glare. The reason for this is that discomfort glare has not been characterized yet, whereas the physical and physiological mechanisms behind veiling and disability glare are much better understood.

Both veiling and disability glares change the luminance contrast of the retinal image, although not in the same manner. Whereas disability glare refers to a scattering of light inside the eye that overlays the retinal image and therefore reduces its luminance contrast, veiling glare is the process in which luminous reflections from specular or semi-matte surfaces reduce the contrast of the visual task physically, modifying the stimulus presented to the visual system [Wienold 2009a; Boyce 2014].

Both veiling and disability glares are therefore due to the presence of bright light in a scene, which is either directed towards the subject's eyes or towards the visual task. Furthermore, the two categories of glare impair the vision in some ways. Conversely, discomfort

glare, which is also due to the presence of bright light in the Field of View (FOV), does not necessarily impair the vision, although it can have a long-term effect on visual performance due to the irritation or distraction it brings. The current knowledge about discomfort glare is summarized in the following sections.

2.1.2 Discomfort Glare

Almost 100 years of research has demonstrated that discomfort glare is a kind of visual discomfort, such as an insufficient amount of light or flicker, that causes discomfort without necessarily impairing the vision of objects [CIE 1983]. However, unlike for veiling and disability glare, there currently exists no solid scientific explanation behind the process of discomfort glare.

Based on our current knowledge, discomfort glare is assumed to be due to two main causes [Iwata et al. 2011a; Hopkinson 1957]. It is indeed defined as a "*condition of vision in which there is discomfort* [...] *caused by an* ***unsuitable distribution or range of luminance****, or to* ***extreme contrasts***" [CEN 2011a] (emphasis added). The two causes of discomfort glare can therefore be described as follows:

- the total amount of light reaching the subject's eyes is too large

  This means that even if the source was seen under a proper contrast with the background, the subject would feel discomfort because her/his eyes could not adapt to the light. This first cause of discomfort glare is called "saturation" or "absolute" glare.

- the contrast between the viewing direction (for example, the visual task) and a bright area in the FOV is too strong

  Either the subject's eyes adapt to the relatively low luminance of the visual task causing the luminance of the glare source to be too high or the subject's eyes are forced to adapt to a bright environment and the visual task is perceived as too dim. This discomfort glare is called "contrast" or "relative" glare.

In order to evaluate or to predict discomfort glare perception, two photometric quantities representing the contrast and saturation effects are implemented as the main variables in discomfort glare metrics. Two other geometrical quantities describing the glare source in the FOV are also taken into account since discomfort glare perception will vary whether the glare source is large or small, and in the central or lateral part of the FOV. Consequently, four physical quantities are commonly used as variables of discomfort glare metrics:

- the **luminance of the glare source**, which is the intensity of the luminous flux emitted per unit area of the source;
- the **adaptation level**, which is defined as either the luminance of the background or the vertical illuminance at eye level, namely, the luminous flux reaching the subject's eye;
- the **solid angle of the glare source**, which expresses the apparent size of the glare source in the hemispherical subject's FOV;
- the **angular displacement of the glare source**, which accounts for the horizontal and vertical displacements of a glare source from the subject's line of vision.

These four variables have been identified by the CIE as the four physical quantities required to evaluate discomfort glare perception [CIE 1983]. However, their respective contributions to the mechanism of discomfort glare have only been proven through statistical inferences based on subjective assessments of discomfort glare and can still not be explained from a physiological or physical point of view. These four variables will be described thoroughly in Section 2.2.1.

By providing a brief history of discomfort glare metrics, Section 2.1.3 shows how the recognition of windows as potential glare sources has gradually led to the inclusion of both the contrast and saturation effects in the metrics. This brief history also expresses, through the numerous discomfort glare metrics that have been developed for different conditions and purposes, the necessity of simplifying the

prediction and evaluation of discomfort glare perception from daylight.

2.1.3 Discomfort Glare Metrics

Discomfort glare metrics, used to evaluate and predict discomfort glare perception, have generally been developed through statistical inferences, in which subjective assessments of discomfort glare are correlated to photometric measurements. Since the 1920s [Luckiesh et al. 1925], researchers have been working on developing such empirical discomfort glare metrics. This subsection provides a brief history of discomfort glare metrics and their equations, in which:

$L_{s,i}$ is the mean luminance of the glare source i [cd/m^2]

$\omega_{s,i}$ is the solid angle subtended by the glare source i [sr]

L_b is the background luminance [cd/m^2]

$f(\theta)$ is the function of the angular displacement of the glare source i from the line of sight [-]

a, b, c are weighting exponents [-]

P_i is the position index related to the glare source i [-]

L_w is the mean luminance of the walls [cd/m^2]

L_f is the mean luminance of the floor [cd/m^2]

L_c is the mean luminance of the ceiling [cd/m^2]

L_s is the mean luminance of the source [cd/m^2]

ω_w is the solid angle subtended by the walls [sr]

ω_f is the solid angle subtended by the floor [sr]

ω_c is the solid angle subtended by the ceiling [sr]

ω_s is the solid angle subtended by the source [sr]

E_{dir} is the direct illuminance [lux]

E_{ind} is the indirect illuminance [lux]

$\Omega_{s,i}$ is the solid angle subtended by the glare source i modified by the position of the source with respect to the FOV and Guth's position index [sr]

L_{avg} is an approximation of the mean luminance through the vertical illuminance (E_v) divided by π [cd/m^2]

L_{adapt} is the mean luminance of the task area [cd/m^2]

L_{win} is the mean luminance of the window [cd/m^2]

ω_{win} is the solid angle subtended by the window [sr]

L_{ext} is an approximation of the mean luminance of the outdoors through the vertical illuminance from the outdoors [cd/m^2]

Ω_{win} is the solid angle subtended by the window modified by the position of the source with respect to the FOV [sr]

L_i is the luminance of the pixel i [cd/m^2]

ω_i is the solid angle subtended by the pixel i [sr]

$L_{s\%2000C}$ is the solid angle ratio of pixels greater than or equal to 2000 cd/m^2 within central and near FOV [-]

L_t is the mean luminance of the visual task area t [cd/m^2]

Discomfort Glare Metrics for Electric Lighting

The first discomfort glare metrics were developed to evaluate discomfort glare perception from lamps i.e., discomfort glare from relatively small glare sources. For instance, experiments in the 1940s were conducted with small incandescent point sources against a uniform background [Luckiesh et al. 1949; Petherbridge et al. 1950]. As small glare sources usually generate discomfort glare due to too strong contrasts, the four main variables presented in the previous subsection were combined as described in Equation 2.1 in those first metrics. The Equation 2.1, which is called the Glare Constant (GC) [CIE 1983], is indeed representative of the contrast effect, being a ratio between the luminance of the glare source and that of the background.

$$GC = \sum \frac{L_{s,i}^{a} \cdot \omega_{s,i}^{b}}{L_{b}^{c} \cdot f(\theta)} \tag{2.1}$$

One example of such contrast-based metrics is the currently recommended discomfort glare evaluation method in the USA, namely the

Visual Comfort Probability (VCP). The VCP was developed based on the studies of Luckiesh and Holladay [Luckiesh et al. 1925] and Luckiesh and Guth [Luckiesh et al. 1949]. It was first published in [IESNA 1973] as described in Equation 2.2.

$$VCP = \frac{100}{\sqrt{2\pi}} \int_{-\infty}^{6.374-1.3227 \cdot \ln DGR} e^{\frac{-t^2}{2}} dt \tag{2.2}$$

In the VCP equation, the Discomfort Glare Rating (DGR) is calculated according to Equation 2.3.

$$\begin{aligned} DGR &= \left[\sum_{i=1}^{n} \left(\frac{0.5 \cdot L_{s,i} \cdot (20.4 \cdot \omega_{s,i} + 1.52 \cdot \omega_{s,i}^{0.2} - 0.075)}{P_i \cdot F_v^{0.44}} \right) \right]^{n^{-0.0914}} \\ F_v &= \left(\frac{L_w \cdot \omega_w + L_f \cdot \omega_f + L_c \cdot \omega_c + L_s \cdot \omega_s}{5} \right) \end{aligned} \tag{2.3}$$

It should be noted that in the VCP equation, as well as in almost all following discomfort glare metrics, the angular displacement of the source from the subject's line of sight is expressed by Guth's position index [Luckiesh et al. 1949].

The VCP evaluates the percentage of subjects that will accept the visual environment as being comfortable. As a general rule, it is considered that discomfort glare is not a problem if the VCP is over 70% [Illuminating Engineering Society of North America (IESNA) 2000].

Another example is the British Glare Index (BGI), sometimes referred to as the Illuminating Engineering Society (IES) Glare Index. The BGI was developed based on the experiments by Hopkinson and Bradley [Hopkinson et al. 1926; Hopkinson et al. 1929; Hopkinson et al. 1960], Hopkinson [Hopkinson 1949; Hopkinson 1963], and Hopkinson and Collins [Hopkinson et al. 1963]. This empirically developed metric also follows the model of contrast-based metrics, as shown in Equation 2.4.

$$BGI = 10 \cdot \log \left[0.478 \cdot \sum_{i=1}^{n} \frac{L_{s,i}^{1.6} \cdot \Omega_{s,i}^{0.8}}{L_b \cdot P_i^{1.6}} \right] \tag{2.4}$$

The BGI outputs a value that is related to one of the four degrees of discomfort glare sensation: Just perceptible, Just acceptable, Just uncomfortable and Just intolerable.

Later on, the CIE Glare Index (CGI), which was originally developed by Einhorn [Einhorn 1969; Einhorn 1979], was chosen as the best available compromise at that time between the different national discomfort glare metrics, and became the recommended discomfort glare evaluation method by the CIE [CIE 1983]. The CGI equation expresses the contrast effect, as shown in Equation 2.5, but the illuminance from the glare source is also included in the denominator. This addition was made to better express the adaptation of the subject's eyes in the case of longer or larger glare sources, such as fluorescent lamps. It was expected that a larger glare source would significantly contribute to the adaptation of the subject's eyes as it would essentially be part of the larger background [Osterhaus 2004].

$$CGI = 8 \cdot \log \left[2 \cdot \frac{[1 + \frac{E_{dir}}{500}]}{E_{dir} + E_{ind}} \cdot \sum_{i=1}^{n} \frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2} \right] \tag{2.5}$$

The CGI categories are mapped to values ranging from 10 to 30, with values over 10 categorized as Perceptible or Noticeable glare, values over 16 categorized as Acceptable glare, values over 22 categorized as Uncomfortable glare, and values over 28 categorized as Intolerable glare [Petherbridge et al. 1950].

To simplify the evaluation of discomfort glare perception, the CGI was replaced by the Unified Glare Rating (UGR) as the recommended discomfort glare evaluation method of the CIE [CIE 1995]. The UGR retains the components of the CGI expressing the contrast effect, as shown in Equation 2.6, but the description of the adaptation level is again reduced to the background luminance without inclusion of the glare sources [Osterhaus 2004]. Accord-

ing to the CIE, this addition had little practical effect when the formula was applied to rooms having illuminances within the usual range recommended for working interiors.

$$UGR = 8 \cdot \log \left[\frac{0.25}{L_b} \sum_{i=1}^{n} \frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2} \right] \tag{2.6}$$

The UGR categories are also mapped to values ranging from 10 to 30, on a glare criterion scale similar to the CGI. Thanks to its simple calculation procedure and its demonstrated reliability, the UGR is gaining wider recognition around the world [Osterhaus 2004].

These discomfort glare metrics are the most common metrics developed to evaluate glare from small sources, hence from electric light sources mainly. They are all contrast-based metrics following the GC model. Daylight discomfort glare metrics have been developed in the continuity of these, as explained in the following subsection.

Discomfort Glare Metrics for Daylighting

With windows becoming larger thanks to better thermal insulation performances and the rediscovery of their potential as a building's heating and lighting system after the 1970s energy crisis, discomfort glare from large sources gradually became an issue as well [Kittler et al. 2012]. In this context, discomfort glare metrics for large sources started appearing.

Hopkinson was the first to develop a metric in order to assess the degree of perceived discomfort glare from windows [Hopkinson 1972]. The equation developed by Hopkinson was actually a modification of the BGI equation, in which the luminance of the glare source is included in the denominator. In case of large glare sources, the adaptation level was indeed thought to be affected by the glare source itself. The large glare source metric developed by Hopkinson was later modified by Chauvel and others to become the Daylight Glare Index (DGI), described in Equation 2.7 [Chauvel et al. 1982].

$$DGI = 10 \cdot \log \left[0.478 \cdot \sum_{i=1}^{n} \frac{L_{s,i}^{1.6} \cdot \Omega_{s,i}^{0.8}}{L_b + 0.07 \cdot \omega_{s,i}^{0.5} \cdot L_{win}} \right] \tag{2.7}$$

The DGI delivers a value between 0 and 30, with 16 and 28 respectively being considered as Just perceptible glare and Just intolerable glare.

In a study to compare the performance of the BGI, the CGI, and the DGI for predicting discomfort glare from large sources, Iwata and others suggested that considering only the contrast effect in wide-source glare metrics might not be appropriate [Iwata et al. 1990]. In the case of large glare sources such as windows, the saturation effect, which was then called the effect of the total amount of light coming into the eyes [Iwata et al. 1992b], becomes significant.

Therefore, Iwata and others developed a new metric to assess discomfort glare perception from windows accounting for both the contrast and saturation effects, which was first called the Glare Sensation Vote (GSV) [Iwata et al. 1992a; Iwata et al. 1992b]. The GSV was revised some years later into the Predicted Glare Sensation Vote (PGSV), described in Equation 2.8 [Tokura et al. 1996; Iwata et al. 2010].

$$PGSV = \begin{cases} PGSV_{sat} = \dfrac{-0.57 - 3.3}{1 + (\frac{L_{avg}}{1250})^{1.7}} + 3.3, & \text{if } \dfrac{L_{win}}{L_b} \leqslant \dfrac{L_{avg}}{L_{adapt}} \\ PGSV_{con} = 3.2 \cdot \log L_{win} - 0.64 \cdot \log \omega_{win} - 8.2 \\ \quad +(0.79 \cdot \log \omega_{win} - 0.61) \cdot \log L_b, \text{ if } \dfrac{L_{win}}{L_b} > \dfrac{L_{avg}}{L_{adapt}} \end{cases} \tag{2.8}$$

The PGSV values range from -0.5 to 3.5, with 0 standing for Just perceptible glare and 3 for Just intolerable glare. The position index is not included in this formula because the glare source, which is the window, is always expected to be in the line of vision of the subject.

The PGSV was the first metric to account explicitly for both of the

causes of discomfort glare, namely, contrast and saturation glare. Thereafter, not only new metrics considering both effects would be developed, but also purely saturation-based metrics would emerge to evaluate discomfort glare perception from daylight.

For instance, Velds observed during laboratory studies with large glare sources that the Vertical Illuminance (E_v), as described in Equation 2.9, was highly correlated with the subjective assessments of discomfort glare [Velds 2000]. A few years later, Wienold made a similar observation [Wienold 2009a]. A recent laboratory study validated the use of the E_v as a daylight discomfort glare metric [Karlsen et al. 2015], endorsing the first purely saturation-based metric.

$$E_v = \text{illuminance measured in a vertical plane} \tag{2.9}$$

Since it only considers the saturation effect, the E_v performs best in situations with large glare sources. In the literature, several studies have led to differing thresholds for this metric, which establish the limit above which the lighting conditions become discomforting. Thresholds going from 1000 lux [Dubois 2001], to 1700 lux [Karlsen et al. 2015], to 2000 lux [Bülow-Hübe 2008; Lee et al. 2007a], to 2800 lux [Konstantzos et al. 2016], to 3359 lux [Wienold et al. 2019], to even 4000 lux [Suk et al. 2013] have been proposed.

While the saturation effect in discomfort glare from daylight was further studied, some researchers focused their efforts on modifying the DGI in order to improve its performance.

First, Nazzal proposed the New Daylight Glare Index (DGI_N) described in Equation 2.10, by redefining the DGI variables in order to be easier to calculate for architects and lighting designers [Nazzal 2001].

$$DGI_N = 10 \cdot \log \left[0.478 \cdot \frac{L_{ext}^{1.6} \cdot \Omega_{win}^{0.8}}{L_{avg} + (0.07 \cdot \omega_{win}^{0.5} \cdot L_{win})} \right] \tag{2.10}$$

The DGI_N is clearly aimed at evaluating discomfort glare perception from daylight, as the luminance of the source from the DGI

equation has been replaced by the luminance of the outdoors. However, the metric still follows the form of a contrast-based discomfort glare metric.

Later, Fisekis suggested modifying the DGI into the Modified Daylight Glare Index (DGI_{mod}), described in Equation 2.11, following the results of a laboratory study [Fisekis et al. 2003].

$$DGI_{mod} = 10 \cdot \log \left[0.478 \cdot \sum_{i=1}^{n} \frac{L_{s,i}^{1.6} \cdot \Omega_{s,i}^{0.8}}{L_{avg}^{0.85} + 0.07 \cdot \omega_{s,i}^{0.5} \cdot L_{s,i}} \right] \tag{2.11}$$

In the DGI_{mod}, the average luminance of the FOV replaces the background luminance originally used as the adaptation level. An exponent smaller than one is applied to the average luminance since it is recognized that, when discomfort glare is due to a saturation effect, the influence of the average luminance in the adaptation term has a declining effect. This modification demonstrates that purely contrast-based metrics are slowly adapted to include the saturation effect in the case of discomfort glare from daylight.

In the same study, Fisekis also investigated the ability of a rearranged UGR formula, namely the Experimental Unified Glare Rating (UGR_{exp}), to evaluate discomfort glare perception from windows. The UGR_{exp}, described in Equation 2.12, considers the two types of discomfort glare, which were then called the "grand total effect" and the "contrast effect" [Fisekis et al. 2003].

$$UGR_{exp} = 8 \cdot \log L_{avg} + 8 \cdot \log \sum_{i=1}^{n} \frac{L_{s,i} \cdot \omega_{s,i}}{L_b \cdot P_i^2} \tag{2.12}$$

In the study, the UGR_{exp} performed very well within the discomfort zone, but the evaluations within the comfort zone were generally overestimated. Through this new equation, another step was made towards daylight discomfort glare metric accounting for both the saturation and contrast effect.

Some years later, Wienold developed a new discomfort glare metric for daylighting, called the Daylight Glare Probability (DGP). The

DGP, described in Equation 2.13, was developed based on a laboratory study with more than 70 subjects assessing glare from a real window [Wienold et al. 2006].

$$DGP = 5.87 \cdot 10^{-5} \cdot E_v + 9.18 \cdot 10^{-2} \cdot \log\left(1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1.87} \cdot P_i^2}\right) + 0.16 \tag{2.13}$$

Similarly to the UGR_{exp}, the DGP contains two terms for the two types of discomfort glare. But contrary to the UGR_{exp}, the DGP was observed to consistently correlate with all the subjective assessments corresponding to the lighting conditions in its validated range. This validated range extends from 0.2 to 0.8.

Furthermore, unlike preceding metrics that evaluated the degree of perceived discomfort glare from daylight, the DGP expresses the probability that a person will be disturbed by glare, by producing values ranging from 0 to 1. Nonetheless, threshold values have later been defined [Reinhart et al. 2011], and allow to use the DGP as a metric evaluating the degree of perceived discomfort glare from daylight: values over 0.35 are categorized as Noticeable glare, values over 0.40 as Disturbing glare, and values over 0.45 as Intolerable glare.

In an attempt to decrease the computational load required to calculate the DGP value, for which each glare source in the FOV has to be identified, Wienold proposed the Simplified Daylight Glare Probability (DGP_s) [Wienold 2007].

$$DGP_s = 6.22 \cdot 10^{-5} \cdot E_v + 0.184 \tag{2.14}$$

The DGP_s only requires one variable, the E_v, in its equation since it was observed that this variable correlated very well with subjects' discomfort glare perception from daylight in the study. However, the use of the DGP_s is limited to visual scenes where no direct sun or specular reflection hits the subject's eyes, since the equation neglects the influence of individual glare sources [Wienold 2007]. By losing the contrast-based term, the DGP_s becomes the second

discomfort glare metric considering only the saturation effect. However, by using the same physical quantity as the first saturation-based metric i.e., the E_v, it should perform similarly.

Another saturation-based metric, the Mean Luminance (L_{mean}), was later proposed by Van Den Wymelenberg as a result of a study testing several existing metrics and other photometric quantities that could be used as metrics [Van Den Wymelenberg et al. 2014]. The L_{mean} is the mean luminance of the FOV as defined in Equation 2.15 [Wienold et al. 2019].

$$L_{mean} = \frac{1}{2\pi} \cdot \sum_{i=1}^{\textit{all pixels in the } 180^\circ \textit{ FOV}} (L_i \cdot \omega_i) \tag{2.15}$$

According to a recent cross-validation study [Wienold et al. 2019], the L_{mean} was one of the best performing metrics when compared against several other saturation-based metrics. The reason for saturation-based metrics better performing in the study is most probably that the subjects had to evaluate discomfort glare in the FOV while sitting next to a large window. The L_{mean} was the third saturation-based metric in the ranking, but the only one based on a luminance value. In the study, the L_{mean} value of 1092 cd/m^2 was associated with Just uncomfortable glare.

At the same time, a second modified version of the UGR was proposed by Hirning [Hirning et al. 2014], since all of the metrics tested in a field study underestimated the subjects' discomfort glare perception. The Unified Glare Probability (UGP) was developed based on one of the tested metrics providing the best correlation with subjective assessments of discomfort glare. The UGP is defined in Equation 2.16.

$$UGP = 0.26 \cdot \log \sum_{i=1}^{n} \frac{0.25 \cdot L_{s,i}^2 \cdot \omega_{s,i}}{L_b \cdot P_i^2} \tag{2.16}$$

The UGP is a linear transformation of the UGR, hence a contrast-based daylight metric. Similarly to the DGP, the UGP calculates a probability of subjects disturbed by discomfort glare from daylight.

More recently, studies have focused on adapting or developing daylight discomfort glare metrics for situations in which the sun is in the FOV, as existing metrics do not perform well in these situations.

Following a laboratory study in which the subjects evaluated discomfort glare from a window with shading fabrics and the sun in the FOV, Konstantzos suggested a modification of the DGP for these specific scenes, the Modified Daylight Glare Probability (DGP_{mod}) [Konstantzos et al. 2016]. The DGP_{mod} is defined in Equation 2.17.

$$DGP_{mod} = 8.4 \cdot 10^{-5} \cdot E_v + 11.97 \cdot 10^{-2} \cdot \log\left(1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{2.12} \cdot P_i^2}\right) + 0.16 \tag{2.17}$$

Konstantzos argued that the general form of the DGP equation is reasonable, but its coefficients should be adjusted to account for different cases. Therefore, the DGP_{mod} should only be used for scenes with the sun in the FOV through window shades.

Similarly, a new metric named according to the glare rating scale, the Glare Sensation Vote (GSV), was proposed for scenes with direct sunlight as a result of a field study conducted by Yamin Garretón [Yamin Garretón et al. 2018]. The GSV is defined in Equation 2.18.

$$GSV = 1.61 + 0.152 \cdot L_{s\%2000C} + 0.019 \cdot \frac{L_s}{L_t} \tag{2.18}$$

The GSV is observed to perform better than the DGP when direct sunlight is present in the work area, but the authors did not report its performance against the DGP_{mod}. Fewer variables are used in this metric in an attempt to simplify the evaluation of discomfort glare perception, but the GSV still includes both saturation and contrast terms. The GSV produces values starting from 1.61, with 2 standing for Noticeable glare, 3 for Disturbing glare, and 4 for Intolerable glare.

This brief history of daylight discomfort glare metrics is not comprehensive, as there currently exist more than 20 of them. The most

common metrics, as well as the best-performing ones according to a recent meta-analysis [Wienold et al. 2019], have been presented.

2.1.4 Efficiency of the Metrics

Although discomfort glare has been studied for almost 100 years now, the evaluation of discomfort glare perception from daylight made by the metrics is still not very efficient. In other words, the daylight discomfort glare metrics do not consistently and accurately match the subjective assessments of discomfort glare made by subjects [Kent 2016].

On the one hand, the evaluation of discomfort glare perception from daylight is not consistent. The inconsistency means that none of the existing metrics can evaluate discomfort glare perception from daylight with constant performance under different conditions. Different studies report different performances of the daylight discomfort glare metrics in different conditions, which makes it difficult to conclude how well the metrics perform.

From a recent meta-analysis study using datasets of different research groups [Wienold et al. 2019], it was shown that the performance of the Daylight Glare Index (DGI) (defined in Subsection 2.1.3), which was evaluated through Spearman's rank correlation between the DGI values and the corresponding subjective assessments of discomfort glare from daylight, varied from 0.32 to 0.64 depending on the dataset.

From this same meta-analysis study, the most robust and best performing daylight discomfort glare metric to date appeared to be the Daylight Glare Probability (DGP) (defined in Subsection 2.1.3). In the results, the DGP could evaluate discomfort glare from daylight with a similar performance for 4 out of the 6 datasets. Still, the performance of the DGP in terms of Spearman's rank correlation in that study varied from 0.37 to 0.68 depending on the dataset.

Furthermore, the performance of the DGP varies significantly between studies in the literature, even though the comparison of the performance of the metrics between studies is hindered by the use of different correlation coefficients (Spearman's rank or Pearson

product-moment) and different subjective assessment methods, by the occasional grouping of data points, by some issues in the light measurement method, etc. For instance, four studies using the Pearson product-moment correlation method obtained a correlation coefficient between the DGP values and the subjective assessments of discomfort glare from daylight of 0.10 [Mahić et al. 2017], 0.37 [Kuhn et al. 2013], 0.51 [Yamin Garretón et al. 2014], and 0.61 [Yamin Garretón et al. 2018]. Although the subjective assessment methods, and potentially other study factors, differ between the four studies, these differences most probably cannot fully explain the large gap between the correlation coefficients. Another example is the variation of the Pearson correlation coefficient between the means of grouped DGP values and the percentages of perceived discomfort, which changes from 0.52 [Konstantzos et al. 2016] to 0.68 [Hirning et al. 2014] when considering around 20 groups of 20 data points.

As the performance of daylight discomfort glare metrics vary significantly from one study to the next, the consistency of these metrics, hence their reliability in evaluating discomfort glare perception from daylight in different conditions, is questioned and needs to be improved. It should be noted, however, that experimental biases, such as the lighting measurement method or the subjective assessment method, might interfere in the results, and cause the variation in the performance of the metrics.

On the other hand, the evaluation of discomfort glare perception from daylight is not accurate. If, instead of comparing the performance of daylight discomfort glare metrics between studies, the performance of these metrics is investigated within a study, a large variation between subjects' discomfort glare perception cannot be explained by the metrics [Matusiak 2013; Karlsen et al. 2015; Boyce 2014; Eble-Hankins et al. 2005; Galasiu et al. 2006; Rodriguez et al. 2014; Stone et al. 1973; Van Den Wymelenberg et al. 2010; Wirtschafter et al. 1966].

Figure 2.2, which is inspired from a demonstration by Kent [Kent 2016], shows the large scatters in photometric or discomfort glare

metric values corresponding to different categories of subjective assessment of discomfort glare that were observed in several studies looking at discomfort glare perception from large glare sources or from daylight.

The large scatters observed in these graphs show that, within a study, and thus in similar conditions for each subject, the daylight discomfort glare metrics do not perform similarly for each subject. Current daylight discomfort glare metrics, which are based only on physical and photometric quantities, are therefore not able to accurately evaluate discomfort glare perception from daylight for any given individual.

Despite the numerous attempts to improve the evaluation of discomfort glare perception through modification and development of new metrics, the large variation existing between subjects' discomfort glare perception can still not be accurately explained. Furthermore, the performance of the metrics still varies a lot between studies. Current daylight discomfort glare metrics cannot consistently and accurately evaluate discomfort glare perception from daylight.

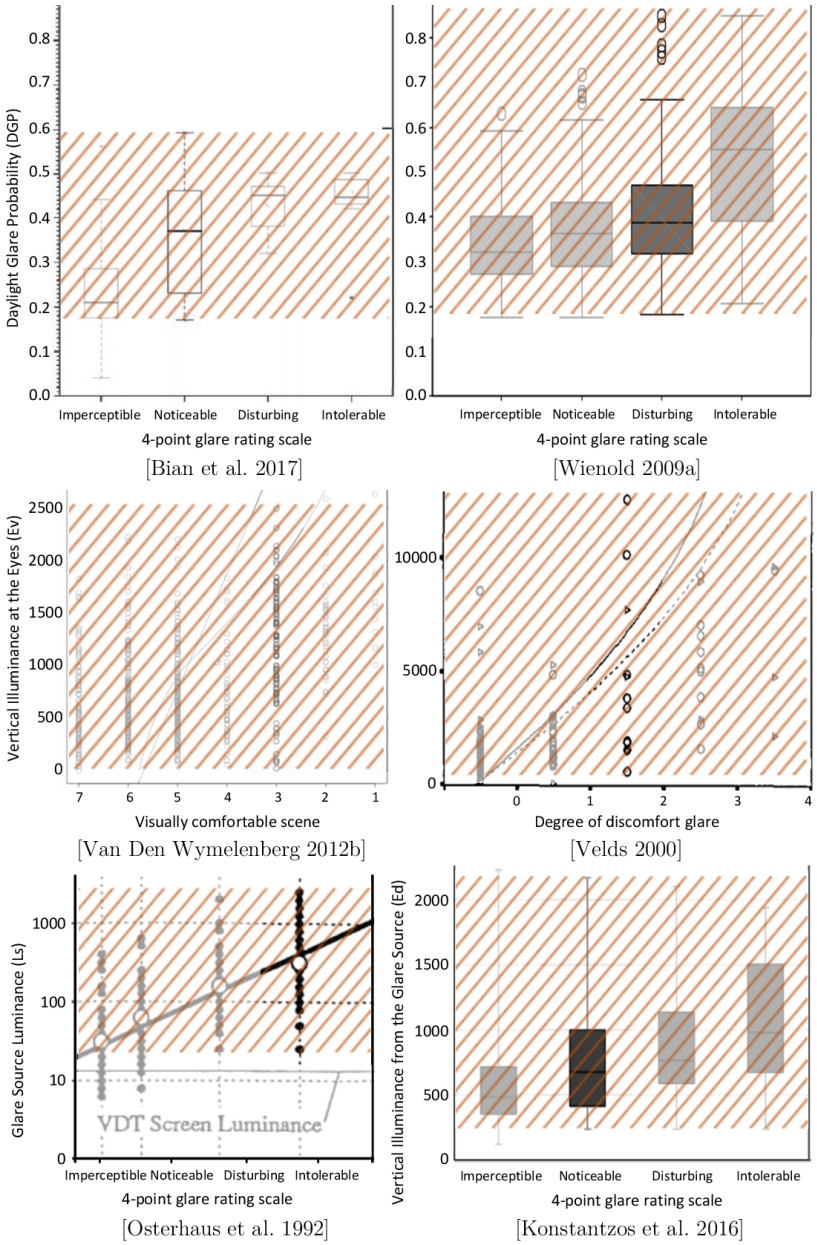


Figure 2.2: Graphical representation of the large scatters in photometric or discomfort glare metric values for different categories of subjective assessment of discomfort glare; the hatched area in each graph represents the largest scatter observable for one of the category of discomfort glare, namely the one that is displayed darker than the others in each graph

2.1.5 Towards the Improvement of the Metrics

The large variation between subjects' discomfort glare perception suggests that other variables than those currently used in daylight discomfort glare metrics, which are purely photometric and physical variables, play a role in the perception of discomfort glare from daylight. This idea is not new. In 1949, Luckiesh and Guth stated that "*the variation between individuals is not unexpected nor extraordinary because of the many physiological and psychological factors which may influence the subjective appraisal of bright areas*" [Luckiesh et al. 1949].

Making a subjective assessment of discomfort glare from daylight requires the expression of a subjective feeling, which is most probably influenced by physiological or psychological processes, as well as contextual elements. Consequently, these additional variables would need to be taken into account to improve the prediction of discomfort glare perception, since they most probably influence it.

Firstly, some personal characteristics of the subject, whether physiological or psychological, could influence the subject's way of perceiving discomfort glare. For instance, studies in the literature have already investigated the potential influence of iris pigmentation on discomfort glare perception [Saur 1969; Bennett 1977; Stringham et al. 2011]. Furthermore, psychological factors such as the emotional state of the subject could also affect her/his tolerance towards discomfort glare, and alter her/his subjective assessment of discomfort glare.

Secondly, indoor environments are multi-sensory environments. The general feeling of comfort of an occupant is therefore influenced by several environmental factors, such as the temperature, the humidity, or the daylight [Torresin et al. 2018; Tiller et al. 2010; Humphreys 2005]. When a subject is asked to assess one of these environmental factors, the other factors might therefore influence in some ways her/his perception. For example, a subject who is already in a discomforting situation because of one specific environmental factor could become less tolerant towards another environmental factor. Environmental factors, but also contextual fac-

tors such as the time of the day, could interact in affecting subjects' perception, and these interactions could be generated either by psychological or physiological processes. Discomfort glare perception from daylight might therefore be influenced by some factors related to the context, such as the air temperature.

Although additional influencing factors related to the subject or to the context would significantly complicate the use of discomfort glare metrics, acknowledging their influence is necessary to better understand the mechanism of discomfort glare perception.

Last but not least, the influence that the study could have on the results should not be neglected. Through the act of studying discomfort glare perception, additional factors related to these studies, which are commonly called experimental biases, could be brought in and distort our understanding of discomfort glare perception. The inconsistency and inaccuracy of the daylight discomfort glare metrics might also be in part due to these experimental biases, which can be multiple, ranging from the subjective assessment method [Kent et al. 2017b; Kent et al. 2018a; Kent et al. 2019; Fotios 2015; Fotios 2018], to the lighting measurement method [Stanley 2016], to the statistical analyses [Uttley 2019], or to the study environment [Pierson et al. 2019b]. Although they would have no impact outside of a study context, these experimental biases should still be investigated since, by potentially influencing the results of discomfort glare studies, they influence the way in which discomfort glare is understood.

To conclude, in addition to the photometric and physical quantities currently used in the metrics, other factors related to the subject and to the context could influence discomfort glare perception. Moreover, experimental biases could affect the results of a study and explain the variation in the performance of the metrics.

For these reasons, a review of factors assumed to have a potential influence on discomfort glare perception from daylight is performed in Section 2.2, as well as a review of experimental biases assumed to have a potential influence on the results of discomfort glare studies in Section 2.3.

2.2 Factors Potentially Influencing Discomfort Glare Perception

In this section, a review of the factors potentially influencing discomfort glare perception from daylight is performed. The criterion upon which a factor is included in the list of potential factors is that at least one study investigated its effect, arguing that the factor could have an influence on discomfort glare perception. However, the listed factors are not always studied under daylight conditions, as some herein-referenced studies used electric light or simulated windows as glare sources.

Thirty-one factors, summarized in Figure 2.3, are classified according to whether they are currently used in daylight discomfort glare metrics, related to the context, or related to the subject. The potential influence on discomfort glare perception of each of these factors is discussed based on the related literature.

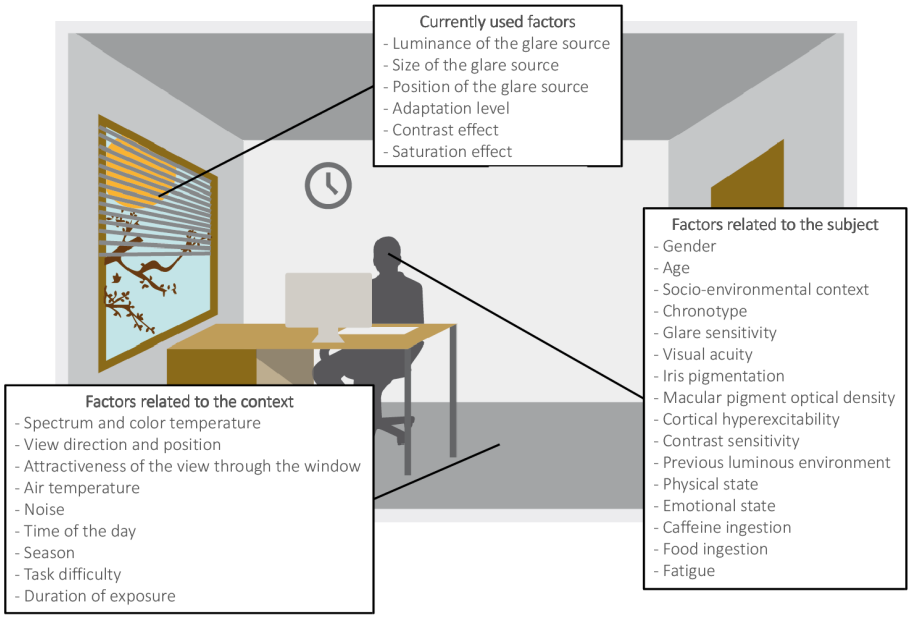


Figure 2.3: Summary of the 31 factors having already been studied in the literature for their potential influence on discomfort glare perception

It should be noted that this list of factors potentially influencing discomfort glare perception from daylight might not be exhaustive. Indeed, in addition to the thirty-one factors listed in this section, other factors, which are still unknown or have not yet been studied, could be involved in the mechanism of discomfort glare perception. These other factors are not considered in the state of the art.

2.2.1 Factors Currently Used in the Metrics

Luminance of the Glare Source

As stated previously, the luminance of a glare source is the source intensity in the subject viewing direction per unit area of the source. Early on, studies conducted to better understand the basic factors influencing discomfort glare perception determined the glare source brightness to be one of the major variables [Luckiesh et al. 1949; Petherbridge et al. 1950]. In his work to summarize the facts on discomfort glare, Einhorn acknowledged that discomfort glare perception increases if the source luminance increases [Einhorn 1969; Einhorn 1979]. A study of Ngai and Boyce [Ngai et al. 2000] confirmed the influence of the glare source luminance some years later. Several studies in road lighting also validated the influence of the luminance of the glare source on discomfort glare perception [Schmidt-Clausen et al. 1974; Bullough et al. 2002; Van Derlofske et al. 2004; Shi et al. 2008; Völker et al. 2017].

Although not mentioned in the brief history of daylight discomfort glare metrics (Subsection 2.1.3), the luminance of the glare source has already been considered as a discomfort glare metric on its own. In this case, it was stated that the higher the luminance of the source, the more glare will be perceived [Carlucci et al. 2015]. Other studies looked at the validity of the luminance of the window as a discomfort glare metric in daylighting [Van Den Wymelenberg et al. 2016; Wienold et al. 2006]. Moreover, glare source luminance thresholds have been suggested in different studies [Bülow-Hübe 2008; Dubois 2001; Lee et al. 2007a; Shin et al. 2012].

However, until now, there has been no universal agreement on these threshold values, and the use of the luminance of a glare source as

a discomfort glare metric alone should be disregarded. Despite the correlation existing between the luminance of the glare source and discomfort glare perception, the luminance of the glare source alone cannot explain discomfort glare perception properly since other factors, such as the adaptation level, the solid angle of the glare source or its position in the FOV have been acknowledged to significantly influence discomfort glare perception.

In most of today's daylight discomfort glare metrics, the luminance of the glare source is not the only variable needed to evaluate the perceived visual discomfort due to glare, but it is certainly one of the most important. However, one essential aspect to pay attention to is the meaning of "the source" when calculating a discomfort glare metric value for daylight conditions. The glare source is naturally thought to be the window when studying daylight discomfort glare. But some years ago, the most common interpretation of the daylight glare source was the luminance of the patch of sky seen through the window [Chauvel et al. 1982; Hopkinson 1972]. Another interpretation of the glare source luminance was the one of Tokura and Iwata who referred to the vertical luminance of the window measured at one point in the center of the window [Tokura et al. 1996]. For the development of the China Glare Index (DGI_{China}) [Huang et al. 2016], Huang and Wang used the average luminance of the entire window. However, during the development of the DGP, Wienold observed that the window luminance did not correlate with subjects' discomfort glare perception [Wienold 2009a]. Therefore, the bright spots in the FOV exceeding four times the task area average luminance, with the task area not containing parts of the window or any glare source, were used as glare sources instead of the window.

The non-uniformity of the window luminance should also be taken into account. The luminance distribution on a window plane will never be uniform in the real world as some parts will always be slightly brighter than others, due to the position of the sun or the clouds. Some obstacles in front of the window can even create shadows, making the range of luminance on the window plane larger. The orientation of the room can also play a role in the

non-uniformity of the window. According to the orientation and latitude of a building, more direct sunlight will hit some of the building façades, while other façades never endure direct sun rays. In a Dutch office building, subjects reported more discomfort glare from windows facing south than east or west. The north orientation was obviously the one causing the least problems with discomfort glare due to direct sunlight [Hellinga 2013].

Moreover, several studies have pointed out that perceived discomfort glare from non-uniform sources is different than from uniform sources. Waters et al. observed that when a subject looks directly at a glare source, non-uniform sources are perceived as more glaring than uniform sources. On the contrary, when the glare source is in the subject's periphery, non-uniform sources are perceived as less glaring [Waters et al. 1995]. Velds partly confirmed this observation as she noticed that when asking subjects to assess their perceived visual discomfort, discomfort glare from non-uniform sources was higher than from uniform sources with identical average luminance [Velds 2000]. Moreover, in a study with real windows, Tuaycharoen and Tregenza pointed out that a view with a wide range of luminance would result in higher perceived discomfort glare than a more uniform view [Tuaycharoen et al. 2007].

Conversely, Mochizuki and Iwata observed in a study with a real window covered with a screen that large glare sources with a non-uniform luminance distribution induced less discomfort glare than uniform glare sources [Mochizuki et al. 2005]. This finding was supported by Eble-Hankins and Waters, as in their study non-uniform glare sources were rated as less discomforting than uniform glare sources [Eble-Hankins et al. 2009]. However, it was also concluded from that study that the contrast spatial frequency of the non-uniform glare sources had a significant effect on discomfort glare perception, and that this effect would vary according to the position of the glare source in the FOV.

This last observation could be an explanation for the contradiction found between the different studies. More recently, several studies having observed an influence of the non-uniformity of glare sources

from electric lighting, such as Light-Emitting Diode (LED) lamps, on discomfort glare perception are working on modifications and alternatives of the UGR for non-uniform light sources [Cai et al. 2012; Donners et al. 2016; Geerdinck et al. 2014; Scheir et al. 2015; Scheir et al. 2017; Tashiro et al. 2015; Yang et al. 2017]. A recent study has even proposed a method to evaluate discomfort glare perception based only on the spatial distribution of the luminance values [Safdar et al. 2016]. In conclusion, the non-uniformity of a window should be taken into account, therefore excluding the luminance of the glare source being defined as the average luminance of the window.

Nowadays, glare sources in a daylit scene are generally defined as the bright spots in the FOV. The challenge still lies in the definition of an objective and universal method to identify these spots [Clear 2013]. A first method was implemented in findglare [Ward 1993]. This method identifies as glare sources every spot in a luminance map of the FOV being seven times higher than the average luminance of this map. More recently, another method was developed by Wienold and Christoffersen to identify glare sources in a luminance map [Wienold et al. 2006]. The algorithm used by the evalglare software recommended for typical office situations calculates the average luminance of a given zone, such as the task area, from a luminance map and points up the spots having a luminance value x-times higher than the average luminance of the reference zone. The task area should not contain parts of the window and, therefore implicitly, any other potential glare source. These spots can then be evaluated as glare sources.

The most advanced and reliable determination method of glare sources so far seems to be the task area method, as supported by a recent study [Pierson et al. 2018a]. This is partly due to the fact that this method takes into account the adaptation process of the eye, but also to the fact that it considers that, in a daylit environment, not only the window can be a source of glare. Daylight reflections might also generate discomfort and should therefore be considered as glare sources as well. This method can, however, lose robustness when the glare source is within the defined task area,

which was explicitly excluded in the original publication of Wienold and Christoffersen [Wienold et al. 2006]. In this case, the glare identification threshold is dramatically increased and the method was demonstrated as being not sensitive enough for glare source detection [Van Den Wymelenberg et al. 2014]. This could be solved by applying other identification methods in these particular situations, such as a fixed glare identification threshold. Moreover, the task area method requires the arbitrary definition of a "threshold multiplier", namely a factor by which the average luminance of the task area has to be multiplied to set the glare detection threshold. Depending on the choice of this threshold, the results of some of the discomfort glare metrics were shown to vary significantly [Sarey Khanie et al. 2015].

In conclusion, the influence of the glare source luminance on perceived discomfort glare is not a matter of debate any more. Recent studies confirm the high correlation existing between the luminance of a glare source and the perceived degree of discomfort glare [Chen et al. 2015; Huang et al. 2017; Lin et al. 2014; Rodriguez et al. 2014; Tyukhova 2015], although this correlation is not large enough to accurately explain discomfort glare perception by itself. The glare source luminance is one of the most decisive factors when assessing discomfort glare, but should not be used as a discomfort glare metric on its own. The reason for this is that other factors are acknowledged to play a role in discomfort glare perception, such as the adaptation level. Moreover, the commonly applied methods to detect glare sources nowadays lack justification and validation, especially in view of discomfort glare metrics solely relying on these glare sources. Further research is therefore needed to clarify the definition of discomfort glare sources. In the meanwhile, an efficient way of validating the glare source detection made by an algorithm is by examining visually the glare sources detected automatically.

Size of the Glare Source

Although there is a clear definition of a glare source missing, the size of it is defined by the solid angle which expresses the width of the source as it appears to the subject eyes. Distance from the

window therefore impacts the way we perceive discomfort glare. The further away we are from the window, the smaller the solid angle subtended at the eye, and the lesser perceived discomfort glare. Velds confirmed this effect as she observed that subjects at the back of the room in a study felt in general less glare than the ones near the façade under similar lighting conditions [Velds 2000]. Aries et al. also concluded from their survey on occupants' well-being at work that the further the occupants sat from the window, the more satisfied they were since they experienced less discomfort glare [Aries et al. 2010].

Since the beginning of discomfort glare research, the solid angle has been included in discomfort glare metrics considering the contrast effect to account for the apparent area of the glare source [Einhorn 1969; Einhorn 1979; Luckiesh et al. 1949; Petherbridge et al. 1950]. Since a glare source is not clearly defined, this indistinctness also impacts the usage of the size of a glare source. Hopkinson mentioned the solid angle subtended by the patch of sky seen through the window to refer to the glare source size [Hopkinson 1972] and was followed by Chauvel et al. some years later [Chauvel et al. 1982]. In the first version of the GSV, the source size is evaluated as the solid angle subtended by the entire window to the point of observation [Tokura et al. 1996]. In evalglare, the solid angle of a glare source is calculated as the sum of the solid angle of the pixels in a luminance map considered as glare sources [Wienold et al. 2006]. As already mentioned, more research is required to build a robust method to define glare sources so that their luminance and solid angle can be evaluated accurately.

The solid angle of the glare source helps to describe the perceived degree of discomfort glare according to the distance of the subject from the source and the size of the source. In the literature, it has been assumed that discomfort glare perception has a negative linear relationship with the distance from the window and a bell-shaped relationship with the size of the window [Boubekri et al. 1992]. Recently, Rodriguez and Pattini concluded from a study with a simulated window that the source size had the same impact on perceived discomfort glare as the luminance of the source

[Rodriguez et al. 2014]. Recent studies have also confirmed that an increased solid angle produced more discomfort from glare [Lin et al. 2014; Tyukhova 2015].

Position of the Glare Source

From the beginning of discomfort glare research, the position of the glare source in the field of view, first evaluated by the angle between the direction of the glare source with the line of sight, was acknowledged as one of the factors influencing discomfort glare perception [Hopkinson 1940]. To account for the difference in the perception of a glare source in relation to its position in the FOV, the position index P was introduced by Luckiesh and Guth in their study on discomfort glare from small sources [Luckiesh et al. 1949]. The index is a function of the vertical and angular displacement of the source from the line of vision of the subject.

Although Petherbridge and Hopkinson did not refer to Guth position index in their studies, they acknowledged the influence of the displacement of the source from the direction of view on discomfort glare perception [Petherbridge et al. 1950]. While Einhorn endorsed the position index as one of the four main variables influencing discomfort glare perception [Einhorn 1969; Einhorn 1979], Hopkinson described it as a function of the angles between the direction of the light source and the subject's viewing direction [Hopkinson 1972]. In the DGI, the position index was determined thanks to the angles subtended by the glare source in the horizontal and vertical directions which were reported on a diagram [Chauvel et al. 1982].

More recently, the vertical position of the glare source in the FOV was again acknowledged as influencing discomfort glare perception from laboratory studies [Chen et al. 2015; Eble-Hankins et al. 2009; Huang et al. 2017; Lin et al. 2014; Tyukhova 2015]. In road lighting as well, it was recognized that the larger the angle from the line of sight, the smaller the glare effect [Schmidt-Clausen et al. 1974; Bullough et al. 2002; Völker et al. 2017].

The PGSV does not include the position index, which means that it only evaluates discomfort glare perceived in the subject's line of

sight [Tokura et al. 1996]. However, in a later study, Iwata and Tokura, investigated the difference between sensitivity to a glare source positioned above or below the line of vision [Iwata et al. 1997]. They deduced, with the help of Einhorn, a new analytical equation applicable to glare sources located below the line of vision as they observed glare sensation was higher than when the source is in the upper part of the FOV. A modified position index was developed including two different expressions reflecting the upper and lower part of the FOV. Evalglare uses this modified position index [Wienold et al. 2006], namely Guth's position index for sources located in the upper part of the FOV and Iwata-Einhorn's for the lower part.

The glare source configuration, which, in the case of discomfort glare from daylight, might have been interpreted as the window configuration, should also be mentioned as a potential influencing factor. Although Chauvel et al. did not find an effect of windows shape on discomfort glare perception [Chauvel et al. 1982], Iwata et al. observed that a simulated rectangular window did not generate the same glare perception to the subjects than a square simulated window, depending on the direction of the view [Iwata et al. 1992a]. However, some years later, Hellinga stated that "*glare perception was not related to the different window configurations*" [Hellinga 2013].

The position of the glare source is considered as a factor influencing discomfort glare perception since the literature agrees on the fact that the further the glare source is from the line of vision, the less is the perceived discomfort glare. Currently, Guth's position index is used in most existing discomfort glare metrics, for daylight and electric light. Further research on the combination of Guth's and Iwata-Einhorn's position index would be needed to confirm its validity. In this respect, several laboratory studies [Kim et al. 2009b; Kim et al. 2005; Kim et al. 2010; Kim et al. 2011] were conducted to develop a new position index, in which the difference between the sensitivity to a glare source positioned above or below the line of vision is implemented. However, there is an inconsistency between the formula and the graph published.

Adaptation Level

The adaptation level can be defined as the light level in a room which sets the adaptation of the eyes to the luminous environment. According to the lighting conditions, the pupil either constricts or dilates, regulating the intensity of light arriving on the retina.

Stringham et al. investigated the effect of the subject's pupil diameter on discomfort glare perception in a study with twenty-six subjects [Stringham et al. 2011]. They discovered a negative relationship between the two. The statistical results indicated that the smaller the pupil diameter was, the higher the discomfort glare was perceived to be, despite a smaller amount of light reaching the retina. This last result might seem paradoxical as it can be assumed that the wider the pupil diameter, the larger the amount of light entering the eyes and the higher the perceived discomfort glare. But the variation of the pupil size should not be looked at as a cause of discomfort glare but as a consequence. The pupil diameter responds to the surrounding luminous conditions. Therefore, when the light in the FOV is very bright, the pupil diameter tends to narrow and filter the amount of light in order to protect the retina.

Two physical quantities have been used to evaluate the adaptation level in discomfort glare metrics:

- the vertical illuminance at eye level

  The illuminance is the total amount of the luminous flux reaching a surface, related to the surface area. The vertical illuminance at eye level provides a measure of the amount of light reaching the subject's eyes. When included in a metric to stand for the adaptation level, the vertical illuminance includes the glare sources.

  The CGI was the first discomfort glare metric in which the vertical illuminance at eye level was used instead of the background luminance to represent the adaptation level [Einhorn 1979]. The illuminance of the scene was also used in a study of Ngai and Boyce instead of the background luminance [Ngai et al. 2000]. More recently, the vertical illuminance at eye level has also been implemented in the denominator of the DGP

formula to account for the adaptation level [Wienold et al. 2006].

- the background luminance

  The background luminance, although more often used in the beginning of discomfort glare research than the vertical illuminance, has been a controversial factor due to the uncertainty about its evaluation. The CIE definition of the background luminance states that the background luminance is "*the uniform luminance of the whole surroundings which produces the same illuminance on a vertical plane at the subject's eye as the visual field under consideration excluding the glare sources*" [CIE 1995]. But in the literature, the definition of the background luminance is not always explicit and might be interpreted differently.

  In the very first studies on discomfort glare from road lighting, the background brightness, namely the background luminance, was defined as the luminance "*of a point* 300 *ft. away on the carriageway*" [Hopkinson 1940]. Luckiesh and Guth then studied the effect of adaptation level by using an "*extended visual field of uniform brightness*" named the field brightness [Luckiesh et al. 1949]. In a laboratory study on discomfort glare from Petherbridge and Hopkinson [Petherbridge et al. 1950], the adaptation level is defined as the "*general background brightness of the surroundings*". Later, Hopkinson invoked the "*surround luminance*" as the adaptation level in an expression assessing discomfort glare [Hopkinson 1957]. Although no clear explanation is given to determine this brightness of the surroundings or surround luminance, it can be deduced that it excludes the glare sources.

  Elsewhere in the literature, the background luminance is also referred to as the luminance of the adapting visual field, which is a "*function of the average luminance of the room interior*" [Hopkinson et al. 1966]. In a later expression of the discomfort glare metric, the background luminance is further defined by Hopkinson as "*the average luminance of the visual field in which the glare sources are seen*" [Hopkinson 1972]. In the

current version of the DGI by Chauvel et al., the background luminance is referred to as "*the average luminance of the interior surfaces of the room which contribute to the visual field of an occupant of the room*" [Chauvel et al. 1982]. From the explanations provided in the appendices of this last reference to measure the background luminance, the glare sources are assumed as not being included in the background luminance evaluation. On the other hand, Hopkinson and Chauvel et al. also mentioned that besides the background luminance, the window luminance should be added in the denominator of the discomfort glare metric expression, since "*the light from the large glaring light source is seen itself to affect the average luminance of the visual field*" and therefore increases the adaptation of the eye [Chauvel et al. 1982; Hopkinson 1972].

More recently, in a study on discomfort glare from daylight, Tokura et al. resorted to the background luminance as the average luminance of the FOV deduced from the vertical illuminance at eye level, minus the luminance of the window [Tokura et al. 1996]. On the other hand, when working on a new version of the DGI, Nazzal recommended the use of the "*adaptation luminance*" instead of background luminance [Nazzal 2005]. The adaptation luminance included the luminance of the window and was evaluated from the vertical illuminance. Kim and Koga recommended the use of the immediate background luminance, defined as "*the luminance of the local background containing the source when the entire background consists of numerous local backgrounds*" instead of the background luminance [Kim et al. 2004]. In road lighting, the average luminance of the road seems to be used as the adaptation luminance [Schmidt-Clausen et al. 1974], although this is refuted by Völker et al. [Völker et al. 2017].

In addition to the fact that there is some confusion about what should be evaluated as the background luminance [Clear 2013], authors seem to disagree on the importance of its effect on discomfort glare perception. In a study with real windows, Iwata et al. made the assumption that the background luminance had a small influence on the perceived degree of discomfort

glare [Iwata et al. 1992b]. Moreover, Saur could not observe any influence of an increased background luminance on discomfort glare perception [Saur 1969]. On the other hand, Kim and Koga concluded from their laboratory study on discomfort glare that "*the background luminance is one of the main factors affecting the degree of discomfort glare*" [Kim et al. 2004]. They added that the threshold luminance bearable by the subjects was mainly determined by the immediate background luminance. Recent studies also confirmed that discomfort glare perception can be significantly decreased with the addition of a luminous surround [Lin et al. 2014; Sweater-Hickcox et al. 2012].

Although nowadays, the background luminance is generally interpreted as the average luminance of the visual field excluding the glare sources [Bellia et al. 2008; Cantin et al. 2011; Carlucci et al. 2015; Jakubiec et al. 2011; Kent 2016; Tyukhova 2015], other interpretations of this background luminance still occur, such as the average luminance of the visual field including the glare sources [Huang et al. 2016], or the average luminance of the visual task [Hirning et al. 2014]. There is therefore a need to clarify what exactly the background luminance is.

In this respect, the CIE defined the background luminance in a more pragmatic way as the indirect vertical illuminance at eye level divided by π [CIE 1995]. Kim and Kim used a similar definition of the background luminance, though replacing the indirect vertical illuminance by the total vertical illuminance, as an estimation of the average luminance of the FOV [Kim et al. 2012b].

However, per definition, the vertical illuminance considers the cosine of the angle of incidence. Therefore, the CIE definition is mathematically not equal to average luminance of the background due to the weighting with the cosine of the angle of incidence. For almost homogeneous background environments, the difference between the mathematical average and the CIE definition is small, and in practice, without impact. But it should be noted that software tools may calculate the back-

ground average luminance differently (e.g., by calculating the mathematical average luminance without weighting the cosine of the angle of incidence).

From the CIE definition of the background luminance, it follows that the main difference between the vertical illuminance at eye level and the background luminance is the inclusion or exclusion of the glare sources in the evaluation of the term. In most discomfort glare metrics for large glare sources using the background luminance, the luminance of the glare source is added in the denominator with a certain weight to account for its effect on the adaptation of the subject's eyes. Therefore, in practice, both methods are similar, except for the weighting of the glare source luminance and the π constant.

Fisekis et al. compared the DGI values for two interpretations of the background luminance, namely, on the one hand, the average luminance of the FOV excluding the glare sources, and, on the other hand, the average luminance of the FOV given by the division of the vertical illuminance by π [Fisekis et al. 2003]. Besides the fact that the double contribution of the source in the adaptation term was considered as a theoretical issue when using the second interpretation, it was concluded that excluding the glare source from the background luminance offered a better evaluation of subjects' discomfort glare assessments overall in the lighting conditions of the study.

In conclusion, there is no doubt as to the influence of the adaptation level on discomfort glare perception according to the literature. What is still debated, however, is the method of defining the adaptation level, and especially for large glare sources covering a wide area in the FOV as these change the adaptation level. Indeed, the adaptation level of the eyes in the case of small sources is mainly influenced by the background luminance (excluding the glare sources). In the case of large sources, the interaction of the glare sources and the surroundings plays a role in the eye adaptation process, as explained by Petherbridge and Hopkinson [Petherbridge et al. 1950]. In the current version of the PGSV, both approaches

are used [Iwata et al. 2011b]; on the one hand, the background luminance excluding the glare sources is used as the adaptation level in the term representing the contrast effect, and on the other hand, the adaptation luminance, evaluated from the vertical illuminance including the glare sources, is used as the adaptation level in the term representing the saturation effect.

Contrast Effect

One of the two types of discomfort glare is related to the contrast between the glare source and the adaptation level. Hopkinson came to this conclusion years ago, distinguishing the contrast effect leading to the relative discomfort glare, from the saturation effect leading to the absolute discomfort glare [Hopkinson et al. 1966]. In most of current discomfort glare metrics, the contrast effect is expressed as a ratio. The ratio between the glare source luminance raised to a certain power and the adaptation level appears for instance in DGI [Chauvel et al. 1982], PGSV [Iwata et al. 2011b], and DGP [Wienold et al. 2006], often associated with the solid angle of the glare source and the position index.

Chauvel et al. acknowledged the ratio between the luminance of the sky and that of the surroundings as being one of the two most important parameters in the assessment of glare from windows [Chauvel et al. 1982]. More recently, Hirning et al. recommended the use of the ratio between the background and the window [Hirning et al. 2017] in discomfort glare metrics, as this ratio was assumed to be a more sensitive parameter of discomfort glare perception than the ratio between the window and the task.

Furthermore, a study from Hansen et al. suggested that certain definitions of luminance ratios, for instance the luminance ratio between the task area and the immediate surroundings, offered better correlations with subjective assessments of discomfort glare in daylit offices [Hansen et al. 2016]. In Carlucci et al.'s review of discomfort glare metrics, the luminance ratio between the central zone of the FOV and the surroundings represented a discomfort glare metric in itself [Carlucci et al. 2015].

In the case of core zones of open-plan offices where discomfort glare is mainly due to contrast, it was also demonstrated that the ratio between maximum window luminance and visual task luminance performed much better at evaluating discomfort glare perception than other discomfort glare metrics [Konis 2014]. Moreover, several studies have been carried out to determine the maximum luminance ratio between the source and the background in order to prevent discomfort glare [Linney 2008; Osterhaus 2009; Veitch et al. 2000].

Saturation Effect

The second type of discomfort glare, the absolute glare, occurs when the amount of light in the FOV exceeds a certain threshold, inducing glare regardless of the contrast in the visual field. This saturation effect has often been evaluated by the vertical illuminance at eye level. Although this term was never taken into account for the evaluation of discomfort glare perception by the CIE, it seems that some authors still relate eye illuminance to visual discomfort caused by glare.

In 1966, Bourassa and Wirtschafter concluded from a study that the discomfort glare threshold is directly linked to the total illuminance on the eyes [Bourassa et al. 1966]. Later on, Sivak et al. found that vertical illuminance at eye level strongly influences discomfort glare ratings [Sivak et al. 1989]. Similarly, during a study on discomfort glare from a real window, Iwata et al. observed that the vertical illuminance at eye level, or the amount of light entering the eyes, had the largest effect on the glare sensation vote [Iwata et al. 1992b]. Velds also found a good correlation between glare assessments and measured vertical illuminance orientated towards the window [Velds 2000].

Kim and Kim used the illuminance at eye level to evaluate an average luminance in the visual field [Kim et al. 2012b]. They observed that the logarithm value of the so-calculated average luminance was in proportional relationship with the perceived discomfort glare values from the entire window. Consequently, they proposed an equation to determine a glare threshold in which the only variable is the

vertical illuminance at eye level. The DGP also includes a specific term representing the saturation effect that uses the vertical illuminance at eye level [Wienold et al. 2006]. The PGSV differentiates between contrast and saturation effects by offering two distinct expressions [Iwata et al. 2011b]. In a study on discomfort glare from a translucent facade with daylight, Matusiak only referred to the vertical illuminance at eye level for measuring glare, and this measure was correlated with the subjects' ratings of discomfort glare [Matusiak 2013]. In road lighting, the vertical illuminance has been several times acknowledged to be a significant variable influencing discomfort glare rating [Sivak et al. 1997; Völker et al. 2017].

Conclusion

To conclude this subsection on factors currently used in discomfort glare metrics, it must be noted that both types of discomfort glare, the saturation and contrast effects, should be considered when evaluating discomfort glare from daylight, as previously recommended [Clear 2013].

Older and somehow more common discomfort glare metrics, such as the DGI, only consider the contrast effect. However, it was demonstrated that when the glare source covers the entire FOV, the DGI cannot properly evaluate discomfort glare perception [Inoue et al. 1989; Iwata et al. 1998a]. Nowadays, more metrics tend to integrate both effects, either through two independent terms or with two different expressions. From the existing discomfort glare metrics, the PGSV, UGR_{exp}, DGP, DGP_{mod}, and GSV consider both types of discomfort glare.

Besides this issue, more research is required to define a clear method to distinguish between the glare source and the background, and more rigor is needed when defining the glare sources and the adaptation level.

2.2.2 Factors Related to the Context

Spectrum and Correlated Color Temperature

As the spectral power distribution or the Correlated Color Temperature (CCT) of daylight can vary with the type of glazing, as well as the weather, time of the day, and season, it is worth studying the influence of these parameters on discomfort glare perception.

Although in one of the first studies of discomfort glare in roads lighting no influence of the color of the light source (whether yellowish, bluish, or white) could be observed on the degree of discomfort glare [Hopkinson 1940], several studies have demonstrated since then that the CCT of the light could have an impact on discomfort glare perception.

A laboratory study from Mochizuki et al. showed that the higher the CCT, the greater the glare sensation [Mochizuki et al. 1997]. In several other studies with car headlights and LED lamps, the glare source or the background color was shown to have a significant influence on discomfort glare perception, as blueish light was always perceived as more discomforting [Berman et al. 1995; Flannagan 1999; Kimura-Minoda et al. 2011; Sweater-Hickcox et al. 2012; Ishida et al. 2011]. Some authors have reinforced this observation by showing that glare sources with a large amount of short-wavelength light resulted in higher perceived discomfort glare [Niedling et al. 2017; Van Derlofske et al. 2004; Bullough et al. 2002; Flannagan et al. 1992; Akashi et al. 2013; Bullough 2009; Fekete et al. 2009; Sivak et al. 2005; Stringham et al. 2003; Yang et al. 2016].

However, it has recently been demonstrated that metameric light sources, namely sources having different spectral power distributions but the same CCT, did not lead to different discomfort glare perceptions [Huang et al. 2017]. This last observation implies that the spectral power distribution is not directly influencing discomfort glare perception, but the CCT is. The influence of the CCT of the light, namely the apparent color of the light, on discomfort glare has recently been demonstrated again in several studies [Chen

et al. 2015; Bommel 2015; Lin et al. 2014; Völker et al. 2017; Wei et al. 2014; Zhang et al. 2013]. However, the influence of the CCT on discomfort glare perception could not be observed in two other recent studies[Ko et al. 2017; Shi et al. 2008].

Subsequently, glazing that filters some parts of the daylight spectrum, such as electrochromic glazing, might have an influence on discomfort glare perception. More research is required to extend the results of these studies on glare sources from electric lighting to discomfort glare from filtered daylight.

View Direction and Position

By changing our view direction or our position, the luminance distribution across the FOV is altered. Some researchers have recently focused on integrating this new variable by developing either view-independent or gaze-driven discomfort glare evaluation methods. The influence of the view direction and position of the subject on discomfort glare perception has indeed already been observed in laboratory and field studies [Hirning et al. 2016; Sekihara et al. 2016].

The first step to take view direction into account in discomfort glare evaluation was made by Jakubiec and Reinhart with the "adaptive zone" [Jakubiec et al. 2011]. They concluded that, for one workplace, only one discomfort glare evaluation should be considered, which is the lowest discomfort glare evaluation of all view directions and positions of the adaptive zone. This is due to the fact that an occupant will select the least disruptive view direction and position within this adaptive zone to minimize the occurrence of discomfort glare for a particular workplace [Jakubiec et al. 2016].

Since this first proposition, several methods to take into account the adaptation possibilities, hence to avoid view-dependent metrics, have been developed based on simulation studies. A first study by Torres and Lo Verso proposed a new glare evaluation method, which should yield comparable performances to the DGP-based approach [Torres et al. 2015]. This new method is based on the cylindrical illuminance, namely the average of all vertical illu-

minances in all directions around a considered point. This method has therefore the advantage of making the discomfort glare analysis view-independent. Another method has also been developed to evaluate daylight discomfort glare by taking into account the adaptation possibility in terms of head rotation [Tsianaka 2018]. The method consists in evaluating daylight discomfort glare metric values in different view directions, and to apply weighting to each value according to the direction of the view in comparison to the neutral line of sight.

A study looked at how much the evaluation of discomfort glare is reduced when accounting for the adaptive zone [Bian et al. 2018]. In this study, it is shown that discomfort glare evaluation might be reduced by around 30% for some specific degrees of freedom in the adaptation zone.

On another note, Vasquez et al. looked at the time spent by a subject in several view directions and the corresponding discomfort glare metrics values [Vásquez et al. 2016]. Although they could not find any relationship between the two, most probably due to the other factors influencing the view direction such as the visual interest, they noticed that the subject seemed to alternate the sight between more and less stressful view scenarios.

A study from Sarey Khanie et al. used a more sophisticated method with a mobile eye tracker and 270° luminance maps in order to derive a gaze-centered luminance map [Sarey Khanie et al. 2017]. A significant difference was noticed between the gaze-driven and fixed-gaze glare evaluation methods when subjects' gaze was exploring the surroundings independently of the task. In the case of a scene with high luminance values, the view seems to avoid extreme regions containing discomfort glare.

On another note, Iwata et al. did not observe any difference in discomfort glare perception between the subjects sitting facing the window or those sitting perpendicular to it [Iwata et al. 2017b]. This unexpected last result might, however, be due to the fact that the subjects were all asked to look at the window before assessing discomfort glare, which made their FOV very similar.

As these studies are quite recent, more research is needed on the influence of gaze and position on discomfort glare perception. Also, a comparison between gaze-driven evaluation methods and ordinary evaluation methods would be necessary, as it was acknowledged in the case of road lighting that glare evaluation methods with a fixed view led to higher glare ratings than methods with a free view [Völker et al. 2017].

Attractiveness of the View Through the Window

As discovered years ago, the view through the window affects the judgment of discomfort glare from windows [Chauvel et al. 1982]. "*There is an underlying conflict in making an assessment in a highly glaring situation if the window has a pleasant view or one with a great deal of interesting information*" [Hopkinson 1972].

One of the first to show a real effect of the view through the window on discomfort glare perception was Osterhaus [Osterhaus 2001]. During a study conducted to identify the factors playing a role in the assessment of visual comfort in daylit office spaces, the results suggested that discomfort glare is less of an issue when there is an appealing view through the window.

Likewise, Tuaycharoen and Tregenza conducted a large study on the effect of the view on perceived discomfort glare from windows [Tuaycharoen et al. 2005]. Their studies showed that the tolerance to discomfort glare is increased when the source is an interesting image rather than a blank screen, and especially increased when the view contains elements of natural scenes instead of urban or man-made views. In order to validate their results, they conducted their studies with real windows and under real daylighting conditions [Tuaycharoen et al. 2007]. They concluded that the best ranked view, namely the most attractive one, is significantly less glaring than the last ranked one which, in turn, is less glaring than the blank view. Moreover, views with natural scenes appeared to be significantly less glaring than urban views, and views with only one "distance layer" produced more glare than views with three "distance layers". Another study of Tuaycharoen in Thailand produced

similar conclusions [Tuaycharoen 2011].

Shin et al. observed from a study with a simulated window that tolerance to discomfort glare was higher for distant views including the sky layer than for near views and, surprisingly, lower for natural views than for man-made or urban views [Shin et al. 2012]. From these observations, a new metric to evaluate discomfort glare perception was suggested in which four characteristics of the view were included [Kim et al. 2012a]. Moreover, during an experiment in a physical model with daylight, Matusiak observed a trend suggesting that subjects reported higher levels of discomfort glare when there was no view through the window than when there was one [Matusiak 2013].

Hellinga concluded from a field study that "*the outside view might only affect the perceived amount of glare if it is very good or very bad, because otherwise other variables play a more important role*" [Hellinga 2013] as no statistically significant correlation was found between occupants' subjective impression of an outside view and their discomfort glare perception. Similarly, in three other studies on discomfort glare under daylight conditions [Hirning et al. 2014; Iwata et al. 2017b], no statistically significant correlation was found with the view attractiveness. However, since many subjects of these studies were satisfied with their view content, these unexpected results could be due to the fact that the view through the window only influences discomfort glare perception when it is very good or very bad.

What should also be considered is the impact that the view through the window can have on the subjects' acceptance of discomfort glare. Wienold noticed during a laboratory study that the acceptance of discomfort glare could increase in order to maintain the view through the window, although discomfort glare perception remains the same [Wienold 2009a]. Kent reported that when subjects reported greater levels of view importance and could set the Venetian blinds to their preferred position, they were able to tolerate higher levels of discomfort glare [Kent 2016]. Therefore, shading controls strategies should be reconsidered in such a way that blinds

do not block the view through the window or that the system can be overruled by the occupants in order for the subjects to keep a visual contact with the exterior [Iwata et al. 2017a].

To conclude, the view through the window has a direct influence on the acceptance and perceived degree of discomfort glare, especially when the subject has a strong opinion about it. Although the latent dimensions used by the subjects to evaluate the view through the window should be further studied based on the insights given by Kent [Kent 2018], two dimensions of the view seem to be of major importance, namely the interest and the extent of the view.

Air Temperature

Few studies have looked at the influence of thermal comfort on discomfort glare perception in office environments.

In 1998, Mochizuki et al. conducted a laboratory study in which subjects were asked to rate discomfort glare from an electric light source while experiencing one of three air temperatures (19.5°C, 24.5°C, and 29.4°C) [Mochizuki et al. 1998]. The results showed that the ratings of discomfort glare increased with the air temperature.

Another study by Yamin Garreton et al. tested discomfort glare perception in three scenarios having different air temperatures (13°C, 20°C, and 28°C) [Yamin Garretón et al. 2015]. The results of this study showed that the subjects had a different tolerance towards discomfort glare when they were outside their thermal comfort zone, with a tendency for the ratings of discomfort glare to increase with the air temperature.

In a study on the interaction of comfort parameters [Laurentin et al. 2000], no influence of thermal conditions on visual discomfort could be found in the case of daylighting. However, the lack of effect might be due to the fact that the maximum temperature in the study was only 3°C above the thermal comfort zone [Inkarojrit 2005].

Discomfort glare perception could be influenced by other environ-

mental factors, such as humidity or noise.

Noise

Acoustic comfort, which is related to noise, might influence subjects' tolerance towards discomfort glare, especially when the subject is in discomfort due to noise.

To date, only one study seems to have looked at the influence of noise on discomfort glare perception [Mochizuki et al. 1998]. No influence of three different noise levels could be found on the ratings of discomfort glare from an electric light source.

However, without additional research, it is not possible to conclude whether or not acoustic comfort affects tolerance towards discomfort glare.

Time of the Day

Depending on the time of the day, our sensation of discomfort glare might fluctuate.

Two studies conducted by Kent et al. under electric lighting conditions first demonstrated that, as the day progresses, tolerance towards discomfort glare increases [Altomonte et al. 2016b; Altomonte et al. 2016a; Kent et al. 2015c; Kent et al. 2015a].

Conversely, a study conducted by Borisuit et al. revealed no evolution of perceived glare sensation for a period of eight hours [Borisuit et al. 2015]. However, no neutral basis was defined to compare the subjective glare evaluations made during the day in this last study as daylight might have been changing but no discomfort glare metrics were calculated.

More recently, Kent et al. conducted another study under daylighting conditions to confirm the effect of time of day on discomfort glare perception [Kent et al. 2017a]. They concluded that the time of the day could be one of the causes explaining the large variation between subjects' discomfort glare perception, since a statistically significant influence of this factor was observed.

Season

A seasonal effect on discomfort glare perception means that depending on the season and its related daylight characteristics, tolerance towards discomfort glare might vary.

Some authors have already suggested that subjects have a higher acceptance of the presence of sunlight in winter than in summer [Christoffersen et al. 2000; Nicol et al. 2006]. In one of Van Den Wymelenberg's studies on discomfort glare, subjects were significantly more sensitive to glare source brightness during fall than during summer, with a difference of approximately 100 cd/m^2 in glare source luminance [Van Den Wymelenberg 2012b]. This effect could, however, also be attributed to post-awake sunlight availability, namely a smaller or larger amount of daylight prior to the study.

A second study investigated the effect of season on discomfort glare perception, as 58 subjects were asked to evaluate discomfort glare from electric lighting in summer or in winter [Ishida et al. 2011]. No effect of the season could be observed in this study.

Based on these studies, the influence of the season on discomfort glare perception seems inconclusive. More research is required, especially since the seasonal influence might overlap with previous luminous environment.

Task Difficulty

In several studies, attention tasks, such as the Stroop test [MacLeod 1991], are used to assess the influence of the visual environment on workers' productivity and concentration. However, some studies [Flannagan et al. 1990; Sivak et al. 1989] have shown that the task required while rating the visual environment could impact this rating. It is thus important to determine whether the perceived discomfort glare is influenced by the presence and difficulty of a task, or the other way around.

Sivak et al. concluded from a study on the influence of a visual task on discomfort glare ratings [Sivak et al. 1989] that more difficult

tasks resulted in more discomforting glare responses, and that the effect was more noticeable at low levels of glare. Flannagan et al. conducted another study to extend these findings [Flannagan et al. 1990]. Besides reinforcing Sivak et al.'s results on task difficulty, they showed that when subjects have to accomplish a visual task, the degree of perceived discomfort glare tends to be higher than when no task is required.

More recently, a study from Altomonte et al. demonstrated that the more difficult the visual task was, the higher the perceived degree of discomfort glare was [Altomonte et al. 2016b; Altomonte et al. 2016a]. This effect was noticed to be more significant at earlier sessions during the day. However, the authors cautioned that the potential interaction with temporal variables could also have affected the glare response, since a direct relationship was found between fatigue and glare response.

Conversely, Osterhaus and Bailey observed in a study on the effects of large area glare sources on discomfort glare perception that when a task was required, subjects tended to be less sensitive towards discomfort glare [Osterhaus et al. 1992].

Furthermore, Kent et al. conducted a recent laboratory study to compare discomfort glare perception between two visual tasks requiring different degrees of cognitive attention [Kent et al. 2018b]. The results showed that the task expected to demand a higher degree of cognitive attention produced a lower degree of discomfort glare for the subject performing the task.

In road lighting, the influence of the task difficulty on discomfort glare perception has been acknowledged, although it is not clear whether more difficult tasks generate higher or lower discomfort glare perception [Völker et al. 2017].

Besides a lot of controversy between these studies, it should be noted that the subjective assessment of discomfort glare takes place after the subject has finished the task in most of the studies. Further research is therefore needed not only on the influence of task difficulty on discomfort glare perception, but also on the difference between subjective assessments of discomfort glare acquired while

performing a task and after it.

Duration of Exposure

To allow the eye to adjust to the lighting conditions, a certain time, called the adaptation time, is needed. Therefore, the duration of exposure to some glaring situation might be a critical factor in a subject's discomfort glare perception.

Hopkinson was the first to study whether the duration of exposure to a glare source has an influence on discomfort glare perception [Hopkinson 1957]. The results of his study showed that momentary exposure produced more discomfort from glare than continuous exposure, although it is not clear whether similar results would have been found with a larger sample of subjects [Kent et al. 2017c].

Regarding the effect of very short duration of exposure, Sivak et al. studied the difference in discomfort glare perception in road lighting between durations of exposure going from 0.125 to 2 seconds [Sivak et al. 1997]. They observed that the longer the exposure duration, the higher the glare rating.

Conversely, a study of Inoue and Itoh showed that the glare rating decreases with the duration of exposure, and reaches a constant value after 30 seconds of adaptation time [Inoue et al. 1989]. This result is in agreement with a study of Iwata et al. on the effect of duration of exposure on discomfort glare from large sources [Iwata et al. 1990]. In this study, it was observed that the glare source was perceived as less glaring thirty seconds after exposure than immediately after it.

According to a study of Mochizuki et al., it seems that the glare rating keeps on decreasing after one minute of exposure, but settles after around eight minutes [Mochizuki et al. 1998].

More recently, in a study of Geerdinck, it was observed that the first assessment of glare was generally a good predictor for the glare perception after one hour, suggesting that a very long exposure time would not influence discomfort glare perception [Geerdinck 2012].

More generally, two laboratory studies were conducted to investi-

gate the influence of duration of exposure, among other factors, on preferred illuminance and preferred CCT [Logadóttir et al. 2011; Logadóttir et al. 2013]. In the first study, no statistically significant differences in preferred illuminance could be found between the evaluation made directly or after five minutes. However, the second study clearly showed a difference in preferred CCT between the group of subjects that was given a 5-minute adaptation time and the group that was not.

Based on these studies, the subjective glare rating seems to first increase to reach a peak after around one or two seconds of exposure, before decreasing until around 8 minutes of exposure, when it stabilizes. For this reason, in all subjective glare assessment experiments, subjects should be given some time to adapt to ambient lighting conditions.

Conclusion

The factors related to the environment can be sub-classified into three categories: those linked to the time, those linked to the environment, and those linked to the activity.

Regarding the factors linked to the time (season, time of the day, and duration of exposure), only the time of the day shows a somewhat likely influence on discomfort glare perception. The review of the literature regarding the two other factors is inconclusive, and calls for further research.

Regarding the factors linked to the activity (task difficulty, view direction and position), they both seem to show some evidence of an influence on discomfort glare perception. However, most of the studies having looked at these factors are relatively recent, and the influence of this factor should be better understood in several years.

Finally, regarding the factors linked to the environment (spectrum and CCT, attractiveness of the view through the window, air temperature, noise), there have been a lot of studies investigating the interaction of discomfort glare with the factors related to the visual environment, namely the spectrum and CCT and attractiveness of the view through the window, but very few on the interaction

with air temperature and noise. As recommended by Torresin et al. [Torresin et al. 2018], more research is needed to define the interactions between environmental factors so that we can better evaluate the general IEQ.

2.2.3 Factors Related to the Subject

Gender

Based on the literature on IEQ, it is not unreasonable to hypothesize that the gender of a subject influences discomfort glare perception. A large survey on IEQ showed that women are more likely to complain about indoor comfort factors than men [Kim et al. 2013]. Moreover, a literature review on the individual differences in thermal comfort suggested that women are more sensitive to and less satisfied with cold exposures than men, although no consistent conclusion could be drawn on whether gender differences regarding comfort temperature exist [Wang et al. 2018].

However, the subject's gender has already been examined as a factor influencing discomfort glare perception in various studies [Iwata et al. 1992a; Kent et al. 2015a; Pulpitlova et al. 1993; Saur 1969; Shin et al. 2012; Sivak et al. 1989; Tuaycharoen et al. 2007]. They all came to the conclusion that discomfort glare perception is the same whether the subject is a man or a woman.

Despite the fact that thermal comfort could differ between men and women, in view of the numerous studies having investigated this factor, it is assumed that gender does not influence discomfort glare perception.

Age

The subject's age is quite a controversial factor in the assessment of discomfort glare.

As age increases, absolute sensitivity to light, contrast sensitivity, and amount of light reaching the retina are reduced, whereas the amount of scatter in the eye increases. Therefore, several authors believe age should have an influence, even a small one, on discomfort

glare [Karwowski 2006; Mainster et al. 2012; Narisada et al. 2004].

Regarding disability glare, the subject's age clearly has an influence. Indeed, it has been demonstrated that the amount of disability glare produced by a glare source increases with age [van den Berg et al. 2009], and this effect can be easily explained through the increase of light scatter in the eye [Boyce 2014]. Consequently, it could be hypothesized that older subjects will perceive more discomfort glare than younger ones, especially for high levels of discomfort glare.

This hypothesis was supported by Bennett, as a significant correlation was found between the subject's age and the BCD in one of his studies [Bennett 1977]. He was the first to develop a formula (Equation 2.19) to modify the evaluation of discomfort glare according to the subject's age, with the Borderline between Comfort and Discomfort (BCD) decreasing for older subjects.

$$BCD = \frac{80000}{Y} \tag{2.19}$$

where:

BCD is the luminance value corresponding to the BCD [cd/m^2]

Y is the age of the subject [years]

Flannagan [Flannagan 1999] and Akashi et al. [Akashi et al. 2013] reinforced the hypothesis that older subjects give generally higher discomfort glare ratings than younger subjects in studies with glare sources from electric lighting. Iwata and Tokura also noticed a difference between younger and older subjects while developing the new position index [Iwata et al. 1997]. Furthermore, laboratory and field studies from Kuhn et al. on discomfort glare from daylighting suggested that the age effect exists but its statistical significance is very low [Kuhn et al. 2013]. Finally, studies in road lighting suggested that older people are less tolerant towards discomfort glare [Olson et al. 1984], although this difference was very small [Völker et al. 2017].

Conversely, a study from Mochizuki et al. asserted that older people were less sensitive to glare from a large source than younger

ones [Mochizuki et al. 1997]. This was reinforced by two more recent studies: in the first one, younger people were more sensitive to discomfort glare than older people [Wolska et al. 2014], and in the second one, glare thresholds were higher for the "aged" group [Facchin et al. 2017].

In several other studies, the age effect on perceived discomfort glare is refuted entirely.

Saur did not observe any effect due to the subjects' age in a study on the physiological aspects of discomfort glare for car users [Saur 1969]. No relation was found between age and ratings in Vos and Van Bergem's study on subjective reactions to emitted light of greenhouses [Vos et al. 1995]. Furthermore, neither Osterhaus [Osterhaus 2001], Shi et al. [Shi et al. 2008], Shin et al. [Shin et al. 2012] nor Hirning et al. [Hirning et al. 2014] found a statistically significant relationship between subjects' age and the perceived degree of discomfort glare in their respective study or survey.

Although in one study older subjects self-reported as statistically more sensitive to brightness, the measured sensitivity to brightness, which was assessed by asking the subject to rate discomfort glare of glare sources from electric lighting, did not reveal a significant difference between age groups [Van Den Wymelenberg 2012b]. Kent et al. studied the age effect as a personal factor influencing discomfort glare perception [Kent et al. 2015c], but could not demonstrate any statistically significant influence due to age.

More recently, a study from Akashi et al. suggested that, compared to a group of younger subjects, there was a large deviation in glare sensitivity for older subjects [Akashi et al. 2017]. They explained that this large deviation depended on the visual characteristics of the subjects since these visual characteristics can cause the subject to be more sensitive to one of the two types of glare, namely the saturation or contrast effect.

From all these studies, it can be concluded that if there is an effect of age on discomfort glare perception, this effect might be weak, or even negligible, and depend more on the visual characteristics of the subject than on her/his age.

Socio-Environmental Context

Although there exist no widely accepted definitions of the term socio-environmental, it is used extensively, and it is assumed that different persons use it in slightly different ways. From an etymological perspective, the socio-environmental context of a subject is related to the society and the natural environment in which this subject lives. In this research, the socio-environmental context is defined as the climate and habitat, including indoors and outdoors, to which a subject has been acclimatized, her/his behavior towards these elements, and her/his expectations about them.

The use of the term "context" is preferred to the term "background", because "background" is linked to the origins and to the past, whereas "context" has a connotation of the present time. Therefore, the context of a person changes for example if this person moves from one place to another. However, as expressed in the definition, a period of acclimatization is required for the subject to be considered as part of a specific socio-environmental context.

In the literature, a model of cross-cultural adjustment exists, which can help in defining the required period of acclimatization. This model was initiated by a study about the acclimatization of Norwegian students who had studied in the USA [Lysgaard 1955], and further developed through other studies thereafter. The degree of adjustment in the model is measured in terms of variables such as comfort or satisfaction with the new environment, attitudes, contact with host nationals, or difficulties with aspects of the new environment [Torbiorn 1982; Lee 2006; Black et al. 1991]

The cross-cultural adjustment model, following a U-curve as shown in Figure 2.4, is composed of four stages: the "honeymoon stage", during which the subject is fascinated by the new culture and excited about all the new and interesting sights and sounds; the "culture shock stage", during which the subject is faced with disillusionment and frustration from living in the new culture on a day-to-day basis; the "adjustment stage", during which the subject gradually adapts to the new culture and learns how to behave appropriately according to the cultural norms of the host country; and the "mas-

tery stage", during which the subject improves her/his ability to function effectively in the new culture [Black et al. 1991].

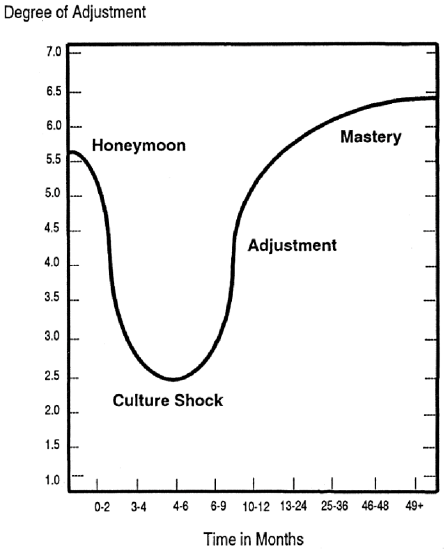


Figure 2.4: U-curve representative of the cross-cultural adjustment model [Black et al. 1991]

Therefore, based on this U-curve of cross-cultural adjustment, a minimum period of two years of living in a specific socio-environment is required for a subject to become acclimatized to that socio-environmental context, as he/she would enter the mastery stage.

In the literature related to discomfort glare perception, several observations made in the last thirty years suggest that the socio-environmental context of a subject, who, it is supposed, is acclimatized to that context, could be a factor influencing her/his discomfort glare perception.

The first observation was made as early as 1964 by Ichikawa and Chonan, as they were reproducing Luckiesh and Guth's original study [Luckiesh et al. 1949] in Japan [Ichikawa et al. 1964]. The results indicated that the arithmetic mean of the BCD brightness for the Japanese subjects was 2903 fL, whereas the arithmetic mean of the BCD brightness in the original study, thus for most probably North American subjects, was 891 fL. This first result demonstrates

a much higher tolerance towards discomfort glare from Japanese subjects.

Later, another observation was made by Subova et al. while they were conducting a laboratory study on the subjective response to discomfort glare in Slovakia [Subova et al. 1991]. From the results of their study, a difference in subjective discomfort glare levels was noticed between the Slovak subjects and the subjects of a similar study carried out in the USA [MacGowan et al. 1988]. It was hypothesized that the difference "*might be caused by a greater sensitivity of the population in Middle Europe adapted to lower luminance conditions*".

Iwata et al. made a similar assumption regarding the difference in tolerance towards discomfort glare between Japanese and British subjects [Iwata et al. 1992a]. In their study, Japanese subjects were reported as being tolerant to higher levels of discomfort glare than the British subjects from a study of Hopkinson [Hopkinson 1971; Petherbridge et al. 1950]. This observation should, however, be tempered since the procedures between Hopkinson and Iwata et al.'s studies were not exactly the same.

Pulpitlova and Detkova carried out another study in Slovakia based on Hopkinson's discomfort glare scale [Pulpitlova et al. 1993]. The mean luminance values evaluated by the Slovakian subjects for each discomfort glare level were similar to those evaluated by American subjects of another study [MacGowan et al. 1986], but differed from the ones evaluated by Japanese subjects of a third study [Iwata et al. 1992a]. This tendency was supported by a laboratory study with 40 Dutch subjects, as the PGSV, a discomfort glare metric developed from laboratory studies with Japanese subjects [Tokura et al. 1996], systematically underestimated the discomfort glare perception of the subjects [Iwata et al. 1998b].

Lee and Kim reinforced the assumption that Asian subjects have a different tolerance towards discomfort glare compared to Caucasian subjects [Lee et al. 2007b]. The DGI thresholds proposed by Hopkinson [Hopkinson 1971] and the ones obtained from their study with Asian subjects were compared, and indicated a significant dif-

ference suggesting that, at high glare source luminance, Caucasian subjects felt more discomfort glare than Asian ones.

In Kent et al.'s study on factors influencing discomfort glare perception, the subject's ethnicity was not correlated with the subject glare perception [Kent et al. 2015b]. This might be explained by the fact that even if the subjects in this study came from various ethnicities, they were all acclimatized to the same socio-environmental context as they lived in the same country. Therefore, the ethnicity factor cannot be accounted for as a socio-environmental context factor.

Recently, a study from Ko and Choi investigated the difference in UGR thresholds between Caucasian and Korean subjects [Ko et al. 2017]. A modified version of the UGR was developed since it was observed that Korean subjects tolerated higher levels of discomfort glare than Caucasian subjects.

On the contrary, from a field study conducted in Indonesia, new thresholds for the DGP were derived [Mangkuto et al. 2017], which are much lower than the original thresholds developed by Wienold et al. for European subjects [Wienold et al. 2006]. This last observation might, however, be related to the difference in tolerance towards discomfort glare between laboratory and field studies, as discussed in Section 2.3.

Furthermore, recent studies have also mentioned the socio-environmental context of the subjects as being a potential limitation of their results on discomfort glare perception [Erell et al. 2014; Jakubiec 2018; Jakubiec et al. 2018], or have aimed at validating current discomfort glare metrics in another socio-environmental context where they had not been studied [Bian et al. 2017].

Finally, a recent study of Iwata was designed to look specifically at the influence of the socio-environmental context of the subject on discomfort glare perception [Iwata 2018]. No significant difference could be observed between the discomfort glare perception from daylight of Middle Eastern and Japanese subjects, who were all students living in Japan. There was, however, no mention of the length of the period during which the Middle Eastern subjects had

acclimatized to the Japanese socio-environmental context.

In conclusion, discomfort glare metrics have been developed up to this point through studies involving particular populations, i.e., British subjects for DGI [Hopkinson 1971], Japanese subjects for PGSV [Tokura et al. 1996], German and Danish subjects for DGP [Wienold et al. 2006]. The discomfort glare metrics have been assumed to be applicable analogously for subjects having different socio-environmental contexts, namely subjects experiencing different climates and having different sensitivities towards daylight.

However, except for the most recent ones, the studies presented here seem to imply that the socio-environmental context of the subject, as defined previously, influences discomfort glare perception. More specifically, it can be hypothesized that subjects acclimatized to the Asian context are more tolerant towards discomfort glare, hence they perceive less discomfort from a specific discomfort glare stimulus, than European or North American subjects.

More studies looking at the influence of the socio-environmental context of the subject on discomfort glare perception are required to provide a deeper understanding of the effect of this factor.

Chronotype

The chronotype of a person is the behavioral manifestation of her/his circadian rhythm, which is regulated by daylight. The behavioral manifestation of the circadian rhythm means her/his propensity to fall asleep at a certain time during the 24-hour loop. An early chronotype person will therefore fall asleep early in the evening and wake up early in the morning.

As the tolerance to glare source luminance became smaller with the progression of subjects' chronotype from early to late type, Kent et al. concluded that earlier chronotype subjects, namely the subjects waking up early in the morning, tolerate higher levels of discomfort glare [Kent et al. 2015a; Kent et al. 2015b].

However, as previously mentioned and despite the promising results of Kent et al.'s study, more than one significant correlation is

needed to acknowledge the influence of chronotype on discomfort glare perception.

Glare Sensitivity

Glare sensitivity is a characteristic that is typically evaluated through self-assessment in discomfort glare studies nowadays. Asking a subject whether he/she often wears sunglasses in sunny weather might help determine whether that person is glare sensitive.

Glare sensitivity most probably resumes from a series of physiological characteristics, but with no further evidence of it and few available methods to evaluate a subject's glare sensitivity objectively, most of the studies having investigated the influence of this factor on discomfort glare perception relied on self-assessed glare sensitivity.

Only in a study of Van Den Wymelenberg [Van Den Wymelenberg 2012b], the self-assessed glare sensitivity, or the self-reported sensitivity to brightness, was compared to the measured sensitivity to brightness. Although the correlation between the self-assessed and measured sensitivity to brightness was rather low, it seemed to hold at the extreme. This means that the subjects of the study could not judge on a multiple-point scale their level of sensitivity, but they could classify themselves into the sensitive or non-sensitive categories.

In 1969, Saur demonstrated that self-assessed glare sensitive subjects have a decreased tolerance of discomfort glare [Saur 1969]. This assumption was confirmed in a survey for which a growing relationship between the average glare experienced and the perceived sensitivity to glare was observed [Osterhaus 2001].

The self-assessed glare sensitivity was also studied as one of the criteria in window-blind control models as it was assumed that this factor could partly explain the wide variability between subjects' discomfort glare perception [Inkarojrit 2005]. However, from the field study, no statistically significant correlation could be observed between the self-reported glare sensitivity and discomfort glare perception.

More recently, Rodriguez and Pattini observed that, when the discomfort glare source lies in the central vision, glare-sensitive people perceived higher discomfort glare than the other group [Rodriguez et al. 2014]. However, this observation could not be confirmed in a second study [Rodriguez et al. 2016b]. Finally, a study from Kent et al. reinforced the assumption that self-assessed glare sensitivity is not a factor influencing discomfort glare perception [Kent et al. 2015a; Kent et al. 2015b].

The influence of the glare sensitivity on discomfort glare perception is not clear as recent studies tend to reject the effect. More research is needed to determine if a subject's sensitivity to glare is related to her/his perception of a discomfort glare stimulus.

Visual Acuity

The subject's visual acuity is her/his ability to resolve detail for a target with a fixed luminance contrast [Boyce 2014]. Generally, a poor visual acuity implies a need for optical correction, namely a necessity to wear glasses or contact lenses. The wearing of glasses or lenses could influence discomfort glare perception as a modification is brought to the eyes of the subject.

First, in a study on the physiological aspects of discomfort glare, no relationship was found between the perceived discomfort glare of a subject and her/his vision correction level [Saur 1969]. In their work on discomfort glare from large sources, Iwata et al. did not detect any significant difference between subjects wearing glasses or lenses and those who did not [Iwata et al. 1992a; Iwata et al. 1997].

In a study on road lighting conducted by Sivak et al., the difference in discomfort glare perception between subjects with optical correction and subjects without correction was not statistically significant, although a tendency was noticed for subjects with optical correction to report more discomfort glare [Sivak et al. 1997].

However, no difference in discomfort glare perception between subjects wearing glasses and subjects without could be found in other studies [Shin et al. 2012; Tuaycharoen et al. 2007]. More recently,

Hirning et al. investigated this effect among others in a large survey, and could also not observe any statistically significant influence on the perceived degree of discomfort glare [Hirning et al. 2014].

It is therefore assumed that the wearing of glasses or lenses does not affect discomfort glare perception.

Contrast Sensitivity

With the ability to resolve fine details, namely the visual acuity, the contrast sensitivity is the other important visual characteristic that refers to the ability of the eye to detect a difference in luminance between an object and its background [Karwowski 2006]. Contrast sensitivity depends on the spatial frequency, namely the frequency of the contrast pattern in the FOV, and the level of contrast.

Several studies have investigated the relationship between contrast sensitivity and disability glare as people often have a loss in contrast sensitivity when there is light scattering in the eyes [Arranz et al. 2014; Bach et al. 2008; Bühren et al. 2006; Paulsson et al. 1980; Siah et al. 2017].

Similarly, contrast sensitivity could have an influence on discomfort glare perception. While the contrast sensitivity curve of the human visual system peaks at a particular frequency and drops on either side of that peak frequency [Hilz et al. 1974], the discomfort glare perception was observed to behave exactly inversely [Eble-Hankins 2008]. From the results of a study conducted by Eble-Hankins, discomfort is minimized at the spatial frequency where contrast sensitivity peaks, and increases on either side of that minimum frequency.

Contrast sensitivity could thus be an interesting variable to study as it could improve our knowledge of the mechanism of discomfort glare.

Iris Pigmentation

The iris pigmentation is the characteristic giving the eye its color. A popular belief is to think that according to their eye color, namely

the iris pigmentation, people perceive glare differently. This belief seems to be based on unfounded assumptions since the iris pigmentation does not play any role in the mechanism of vision, and therefore probably not in the mechanism of glare either.

Nonetheless, some studies have examined the influence that iris pigmentation could have on discomfort glare perception.

In a study on discomfort glare for road safety, no correlation could be found between eye color and the luminance level at which subjects felt discomfort glare [Saur 1969]. This result was supported by a laboratory study, in which no difference in discomfort glare perception could be observed between subjects with light-colored and dark-colored eyes [Iwata et al. 1998b].

Contrariwise, in a survey conducted by Osterhaus, a slight indication suggested that "*workers with lighter eye colors might, on average, perceive to be slightly more sensitive to glare and might be experiencing slightly higher levels of glare*" [Osterhaus 2001]. But this information was not verified against discomfort glare metrics evaluations, and it could instead be linked to the fact that subjects with light eyes are biased by the popular belief, and consider themselves as more sensitive to glare. Another similar trend of iris pigmentation influencing glare perception was reported in a study with a glare source from electric lighting, as subjects with dark eyes reported lower discomfort glare perception [Bennett 1977].

However, the effect was later refuted in a study to determine the effect of retinal pigment on visual discomfort [Stringham et al. 2011]. It was concluded from this study that the iris pigmentation has no statistically significant influence on the perceived visual discomfort despite a visible trend. Recently, Rodriguez et al. [Rodriguez et al. 2016b] noticed that more light-eyed volunteers were found in the glare-sensitive group than in the glare-insensitive group in one of their studies. But no statistically significant difference in discomfort glare perception could be found in the study between glare-sensitive and glare-insensitive subjects.

Despite tendencies indicating that light-eyed people could be more sensitive to discomfort glare, there is so far no statistically signif-

icant evidence that iris pigmentation influences discomfort glare perception. Additional studies focusing on this particular matter should be conducted to confirm or disprove this hypothesis.

Macular Pigment Optical Density

Macular Pigment Optical Density (MPOD) is the density of pigments in the macula. The macula is a small area located in the retina where cones, which are the photoreceptors mainly responsible for photopic vision, have the highest density. The transparent yellow pigments in the macula are derived from carotenoids, and deposited in this photoreceptor axon layer. A high MPOD level protects the most important part of the retina as the macular pigments absorb high-energy short-wavelength light [Boyce 2014].

The effect of MPOD on visual discomfort, and specifically on discomfort glare, has been studied several times.

From a study on the relationship between subjects' discomfort glare thresholds and spatial distribution of macular pigment in the retina [Stringham et al. 2004], it was assumed that macular pigment acted as a spatially integrated filter against short-wavelength light and that a person with a relatively high macular pigment level perceived less discomfort glare in the central viewing.

Another study from Stringham et al. showed that subjects with broader MPOD spatial distribution perceived less discomfort glare [Stringham et al. 2011]. They therefore hypothesized that subjects having relatively high macular pigment levels would tolerate more intense lights. The assumption that macular pigments reduce discomfort glare by absorbing short-wavelength light was endorsed by Lien and Hammond [Lien et al. 2011].

However, Loughman et al. conducted another study on the role of MPOD, and concluded that visual performance under glare conditions was not related to MPOD [Loughman et al. 2010].

No definitive conclusion can be drawn from these studies on the effect of MPOD on discomfort glare perception, as the MPOD mechanism towards discomfort glare is not well understood.

Cortical Hyperexcitability

The cortical hyperexcitability is the degree of activity of the neurons in the visual cortex, namely the neural tissues composing the outer layer of the part of the brain responsible for vision. The neurons actually mediate communications of the nervous system by propagating electrical signals generated by their excitable membrane.

One study has shown that the cortical hyperexcitability of a subject, meaning the degree to which her/his neuronal activity can arise, influences her/his sensitivity to discomfort glare [Bargary et al. 2015]. The authors observed that the glare-sensitive subjects showed significantly greater activity in the visual cortex. Moreover, the data suggested a positive correlation between the magnitude of the neuronal response and subjects' sensitivity to discomfort glare.

This neuronal effect on discomfort glare perception could in part explain the difference existing between glare-sensitive and glare-insensitive individuals. These two factors, namely the neuronal effect and the self-assessed glare sensitivity, might therefore overlap. Only one of them should be taken into account as a new variable of discomfort glare models. The self-assessed glare sensitivity, despite its lack of accuracy, might be easier to evaluate, and thus to use, than the cortical hyperexcitability.

Previous Luminous Environment

The previous luminous environment stands for the lighting conditions that a subject experienced during the period preceding the assessment of discomfort glare, whether it is the previous minutes, hours, days, weeks, or even longer.

A statistically significant correlation was found between one's occupation environment type, namely whether a person works inside or outside, and the BCD level [Bennett 1977]. Bennett observed that subjects experiencing a lot of daylight at work, and therefore during the days preceding the glare evaluation, have a higher tolerance towards discomfort glare.

Inoue and Itoh conducted a laboratory study with a uniform glare source from electric lighting to test the effect of pre-adaptation luminance, namely the luminance experienced during the minutes preceding the glare evaluation, on discomfort glare perception [Inoue et al. 1989]. The pre-adaptation luminance had a significant influence on discomfort glare perception just after the subjects changed their visual field, but faded as the subjects became adapted to the new lighting conditions. A similar study was conducted by Iwata et al. with a real window [Iwata et al. 1992b]. However, no difference could be found between the degrees of discomfort glare for two different pre-adaptation luminance values. The lack of difference was assumed to be related to the rather low difference in pre-adaptation luminance values (110 cd/m^2 and 220 cd/m^2).

Looking at longer periods of pre-adaptation luminance, another laboratory study suggested that whether a subject had spent the last day in a shadowed or overlit environment, her/his discomfort glare thresholds were significantly different [Pulpitlova et al. 1993]. Kent et al. also observed in their study that subjects having experienced daylight in the morning tolerated a slightly higher degree of discomfort glare but this effect could not be demonstrated as statistically significant [Kent et al. 2015a; Kent et al. 2015b]. A direct trend between discomfort glare perception and prior light exposure was deduced from a similar study, especially on glare evaluations made in the evening [Altomonte et al. 2016b; Altomonte et al. 2016a].

No strongly significant evidence towards higher tolerance of discomfort glare for subjects having previously experienced daylight could be demonstrated, although a tendency was observed. Additional research is needed to determine whether this effect is real and whether short-term, post-awake, previous day, or previous week sunlight availability has more influence on discomfort glare perception.

Physical State

Since physical conditions such as diseases, head pain, or back pain, can reduce the sensation of comfort, these could also impact the

perceived visual comfort of a subject and influence her/his discomfort glare perception in a negative way.

When asking subjects about their current physical state in a survey on discomfort glare sensitivity, no influence of the physical state could be found on discomfort glare perception [Osterhaus 2001].

However, only one survey investigated this factor and the subjective results were not compared to measures of the lighting environment or discomfort glare metrics. More research is therefore required to confirm that the way a person feels physically does not influence her/his discomfort glare perception.

Emotional State

The current emotional state of a subject could affect her/his discomfort glare perception in the sense that positive emotions such as joy, serenity, pride or amusement could lead the subject to be less critical of the lighting conditions. The opposite could be true for negative emotions.

Similarly to the physical state, when asking subjects about their current emotional state and their sensitivity to discomfort glare, no correlation could be found with frequency of discomfort glare perception [Osterhaus 2001]. However, a small influence was observed in another study establishing that, surprisingly, subjects in a better mood would experience slightly higher discomfort from glare [Altomonte et al. 2016b; Altomonte et al. 2016a].

More research is needed to confirm or discount the assumption that subjects' emotional state has an influence on discomfort glare perception.

Caffeine Ingestion

When associated with bright light exposure, caffeine ingestion has an effect on melatonin secretion and therefore on the circadian rhythm (Wright et al. 1997). In this regard, caffeine ingestion could also have an influence on discomfort glare perception.

Two studies investigated the temporal factors influencing discomfort glare perception, including caffeine ingestion [Altomonte et al. 2016b; Altomonte et al. 2016a; Kent et al. 2015a; Kent et al. 2015b]. According to their results, there is a tendency for the subjects not having ingested caffeine to report discomfort glare at higher levels of glare source luminance.

However, more results are required to confirm this hypothesis.

Food Ingestion

Since circadian rhythms can be affected by time-dependent schedules of light exposure, caffeine, and food intake [Kent 2016], the ingestion of food prior to glare evaluation has also been studied for its influence on discomfort glare perception.

No statistically significant influence could be found in Kent et al.'s study [Kent et al. 2015a; Kent et al. 2015b]. A significant difference was observed in another study between subjects having ingested food and those who had not, although this difference was below the threshold of practical relevance [Altomonte et al. 2016b; Altomonte et al. 2016a].

The influence that food ingestion could have on discomfort glare perception is not clear, and further studies should be conducted to dismiss or endorse this factor.

Fatigue

Fatigue could influence discomfort glare perception, as tired subjects could be less tolerant towards discomfort glare in their FOV [Kent 2016].

From two laboratory studies, some effects of fatigue of small but relevant size were detected, with a higher tolerance to luminance levels for less tired subjects [Kent et al. 2015a; Kent et al. 2015b; Altomonte et al. 2016b; Altomonte et al. 2016a; Kent 2016].

These small fatigue effects do not allow, however, conclusions to be drawn on the influence of subjects' perceived level of fatigue on discomfort glare perception. Moreover, it is well likely that fatigue

and time of the day are dependent factors. Attention should thus be paid to these factors so that they do not overlap each other.

Conclusion

In summary, there are three categories of factors related to the subject: those linked to demography, those linked to the visual system, and those linked to the present state of the subject.

Some factors linked to the visual system, such as visual acuity, contrast sensitivity, iris pigmentation, MPOD, or cortical hyperexcitability, might influence discomfort glare perception due to a mainly physiological process. Therefore, it is necessary that these factors be studied through rigorous clinical studies in which physiological characteristics can be accurately determined. Since few such studies have been conducted up to now, the influence of these factors as well as the physiological mechanism of discomfort glare are still very unclear at present.

On another note, some factors linked to the present state of the subject, such as the physical state, the emotional state, or the fatigue, might influence discomfort glare perception due to a mainly psychological process. More studies should be aimed at investigating these potential factors given that research on this topic is still very limited. Furthermore, it would be appropriate for these studies to be conducted in collaboration with psychology experts, so that the assessment methods to determine these factors are accurate and validated.

Finally, regarding the factors linked to demography, the two most common ones, namely gender and age, have been extensively investigated. More studies should now look at the socio-environmental context and the chronotype, as both of them seem promising factors to further explain discomfort glare perception, but very few studies have been dedicated to investigate their influence.

2.3 Potential Experimental Biases

In this section, a review of the potential experimental biases influencing the results of discomfort glare studies is performed. The criterion to discuss an experimental bias is that at least one study investigated its effect, arguing that the experimental bias could have an influence on the results of discomfort glare studies. Seven experimental biases are thus reviewed.

It should be noted that this list of potential experimental biases for discomfort glare studies might not be exhaustive as other biases, which are still unknown or have not yet been studied, could also affect the results of discomfort glare studies. These other experimental biases are not considered in the state of the art.

Glare Rating Scales

The method used for the subjective assessment of discomfort glare can become an experimental bias and influence the results of a study if it is not correctly designed. To evaluate discomfort glare perception, researchers up to now have relied on feedback from the subjects collected via questionnaire. The subject is usually asked to evaluate her/his discomfort glare perception through glare rating scales, such as De Boer's glare rating scale [De Boer 1967], Hopkinson's glare rating scale [Hopkinson 1940], or the GSV [Iwata et al. 1992a]. Several elements of these glare rating scales could somehow influence the subjective assessment made by the subject, such as

- the scale bias towards higher glare assessments
  Glare rating scales used to evaluate discomfort glare might lead a study subject to acknowledge the presence of glare since "no glare" is often not a choice in the possible responses of the scale [Fotios 2015]. subjects' answers are thus biased as the reported perception is somehow imposed. Moreover, when asking questions about glare itself, the attention is drawn on it, forcing the glare option [Van Den Wymelenberg 2014]. In general, the act of asking subjects to rate something incites

them to acknowledge this thing, which they might not have considered in other conditions.

- the interpretation of scale labels

  The various labels of existing glare rating scales may be interpreted in different ways, either between different subjects taking part in a study, or between subjects and researchers [Olson et al. 1984; Fotios 2015; Kent et al. 2017c; Rea 1982; Van Den Wymelenberg 2014]. For instance, a study investigating De Boer's glare rating scale showed that the descriptor *Satisfactory* was most of the time misunderstood [Gellatly et al. 1990]. Another study showed a significant difference in interpretation between the perception and acceptance ratings of discomfort glare [Geerdinck 2012]. According to these results, a setting that is acceptable is not necessarily comfortable, suggesting that these two concepts should not be merged in a single scale such as in De Boer's scale.

- the number of scale response points

  With the large number of existing glare rating scales, it is unclear how many response points should be preferred for these scales. Glare rating scales in the literature have between four and ten response points [Osterhaus et al. 1992; Fisekis et al. 2003; Tuaycharoen et al. 2007; Shin et al. 2012; Carlucci et al. 2015; Stringham et al. 2011], and this variation in scale formats might have an influence on subjects' subjective assessments [Fotios 2015]. Although still debated, the number of scale response points and its related biases have already been studied in the literature for other research fields [Garland 1991; Weijters et al. 2010].

Anchor Bias

When using an adjustment method to evaluate discomfort glare perception, several authors have suggested that an anchor bias would interfere.

The adjustment method in discomfort glare studies requires a subject to adjust the brightness of the glare source (or of the back-

ground lighting), until a predefined criterion of discomfort glare perception is reached. The glare source is thus set at a specific brightness, namely the anchor, before the subject adjusts it. This anchor tends to bias the subjective assessment of discomfort glare. For instance, a low anchor will result in substantially lower subjective assessments.

Regarding lighting studies in general, this issue was first reported in a laboratory study with 26 subjects [Osterhaus et al. 1992]. The subjects preferred higher luminance values for the surround of a glare source when they were presented with high initial luminance values.

Almost twenty years later, Fotios and Cheal conducted a laboratory study using the adjustment method to investigate several potential experimental biases of lighting studies, including the anchor bias [Fotios et al. 2010]. They observed that the mean preferred illuminance was higher when starting from a high initial illuminance rather than from a low one. The effect of anchor bias was further studied in three studies on preferred illuminance and preferred color [Logadóttir et al. 2011; Logadóttir et al. 2013; Uttley 2019]. In all studies, the anchors affected the subjects' preference settings, with high anchors leading to higher preferences for illuminance and color [Fotios et al. 2011].

The effect of anchor bias in discomfort glare studies was recently investigated. Kent and others warned about the potential influence of an anchor bias on results of previous discomfort glare studies [Kent et al. 2017c], before conducting a study using an adjustment method to look at this potential experimental bias [Kent et al. 2017b]. The results of their laboratory study with 22 subjects showed a significant bias of the glare settings adjusted by the subjects towards the luminance of the initial anchor.

Order Bias

Similarly to the anchor bias, an order bias could affect the results of a study when using an adjustment method to evaluate discomfort glare perception. The order bias would cause the current setting

to be influenced by the preceding ones when a subject is asked to adjust the brightness to match predefined criteria of discomfort glare perception in a specific ascending or descending order.

This issue was first identified from the results of past studies on discomfort glare in the literature by Kent et al. [Kent et al. 2017c]. Consequently, they conducted two laboratory studies to validate the effect of order bias on subjective degrees of discomfort glare: the first one with a small glare source from electric lighting and 20 subjects [Kent et al. 2018c], and the second one with a large glare source from electric lighting and 55 subjects [Kent et al. 2018a]. The two studies showed similar results: there was statistically significant and practically relevant evidence of an effect of order bias in the discomfort glare evaluations made by test subjects. This is explained by the fact that settings are biased towards the condition prevalent at the outset of the adjustment (anchor bias), and if the first setting is overestimated, all the following settings will tend to be overestimated as well.

Stimulus Range Bias

In the field of lighting, and especially for studies using the adjustment method, the stimulus range available to the subjects of a study has been shown several times to have a significant influence on the subjective assessments of the visual scene. Therefore, the subjects' subjective assessments could not be used as an absolute result for the studies affected by this experimental bias, but as a relative result depending on the range of other settings.

Lulla and Bennett were the first to demonstrate the influence of the stimulus range bias on the subjective assessment of discomfort glare from electric lighting [Lulla et al. 1981]. The results of their laboratory study with 40 subjects demonstrated that the BCD for the subjects experiencing a stimulus range of 3 to 10^6 cd/m^2 was achieved at a glare source luminance of $92 \cdot 10^3$ cd/m^2, whereas for those experiencing a stimulus range of 3 to 10^5 cd/m^2, the BCD was achieved at a glare source luminance of $13 \cdot 10^3$ cd/m^2.

Several lighting studies using an adjustment method were con-

ducted to show the effect of the stimulus range bias on preferred illuminance and preferred color [Fotios et al. 2010; Fotios et al. 2011; Logadóttir et al. 2011; Logadóttir et al. 2013]. The results show that the mean preferred illuminance or color tend to lie in the middle of the available stimulus range, regardless of what that range is.

More recently, Kent et al. again drew attention to the effect of the stimulus range bias on the results of discomfort glare studies [Kent et al. 2017c]. They conducted a laboratory study with 42 subjects to demonstrate the influence of the stimulus range on the settings of discomfort glare with a simulated window [Kent et al. 2019]. Their results indicated that the stimulus range had a significant effect on the settings made, as the mean luminance associated with a Just intolerable discomfort glare for the low range subjects was less than that associated with a Just uncomfortable discomfort glare for the high range subjects.

Furthermore, the stimulus range bias has not only been demonstrated in studies using the adjustment method, but also in studies using glare rating scales. Olson and Sivak conducted a laboratory study in which two ranges (a large and a partial one) of discomfort glare stimuli were presented at two groups of subjects, who had to assess the level of discomfort glare on De Boer's glare rating scale, in a random order [Olson et al. 1984]. For the same stimulus, the subjects exposed to the partial range reported higher levels of discomfort glare than those exposed to the full range, especially at high glare levels. These results are supported by those of a study from Geerdinck et al. on discomfort glare from electric lighting [Geerdinck et al. 2014]. In that study, the acceptance rating of a specific discomfort glare stimulus was observed to differ according to the range of other stimuli displayed to the subjects. They concluded that the absolute value of a response to a specific setting depends on the set of light settings that was offered to the subject.

Practically, the stimulus range bias means that the rating given by a subject maps to the range of available stimulus magnitudes. Depending on the stimulus range presented, a situation might be

rated as comfortable in one study and uncomfortable in another one. This is due to the fact that subjects tend to make relative evaluations based on the available stimulus range, or even based on well-known or personal standards [Poulton 1977].

Study Type

The literature seems to show that subjects have a different tolerance towards discomfort glare depending on whether the study takes place in a laboratory environment or in the field.

In road lighting, it has been observed that discomfort glare is assessed more critically in a laboratory test than in a full-scale vehicle meeting situation, except at very high intensities [Olson et al. 1984]. This observation was confirmed in a recent literature review on factors influencing discomfort glare perception in road lighting [Völker et al. 2017].

More research is therefore required to determine whether this study type bias might also affect the results of studies on discomfort glare perception from daylight and why.

Conclusion

These potential experimental biases are all reasons to pay special attention when designing a study on discomfort glare, especially since the list is most probably not exhaustive. Recommendations similar as those available in [CIE 2014], i.e., the use of a control situation or sequence randomization, should be adopted to reduce the probability of influence of these factors on the results.

Moreover, as it has been demonstrated for the stimulus range bias, an anchor bias or an order bias might as well affect the results of discomfort glare studies using methods other than the adjustment one. More research is required to further study the effect of anchor and order bias in discomfort glare studies.

2.4 Summary

2.4.1 Likelihood of Influence of the Factors and Experimental Biases

All factors and experimental biases having been the object of at least one study for its potential influence on discomfort glare perception or on the results of discomfort glare studies have been reviewed. They are classified according to whether they are currently used in discomfort glare metrics, related to the context, related to the subject, or a potential experimental bias.

To summarize these factors and biases, they are all listed in Tables 2.1 to 2.4, with the reference of the authors who investigated them in a chronological order.

To get a hint of the size of each study referenced, the "Subjects" column contains the number of subjects having taken part in the study. The "Evaluations" column gives the total number of glare evaluations if the study referenced is a field or laboratory experiment, namely a study involving subjective evaluations compared to physical measurements of glare. The total number of glare evaluations is the number of subjects times the number of conditions times the number of subjective glare evaluations per condition.

If the published study consists in a literature review or presents results from several past studies, an "R" is used to indicate that the sample size and the number of glare evaluations cannot be displayed. An "S" in the Evaluations column indicates that the study is based on a survey, and no physical measurements of glare were collected. When the glare evaluation is made objectively, namely when glare perception is measured through a physiological response rather than evaluated by the subject [Iodice et al. 2017], this is indicated by an "O". If the number of subjects, glare evaluations, or influence direction could not be determined from the publication, a "?" is used in place of the missing information. Finally, a "P" means that the influence of the factor deduced from the publication does not refer to the study, but to the authors' point of view.

Furthermore, the "Influence" column indicates whether an influence of the factor on discomfort glare perception is endorsed ("V") or denied ("X") by the study referenced. For all studies supporting the influence of a factor, additional information is given in the "Direction" column. This column gives an overview of the agreement rate on the direction of the influence (increase or decrease of discomfort glare perception). For instance, two "A" letters in this column for two studies having investigated the same factor mean that the two studies agree that discomfort glare perception is reduced (or increased) by the factor in question.

Finally, an "Indicator" is proposed to express the likelihood (or unlikelihood) of the influence of the factor on discomfort glare perception. This indicator is based on the number of studies supporting or rejecting the influence of the factor as well as the sample size of the experiments.

Specific rules have been defined to classify each factor and experimental bias in a category of the influence indicator. In these rules, the large experiments refer to field and/or laboratory experiments with sample size of 30 subjects or more, whereas studies include review studies, surveys, and the other field and/or laboratory experiments. The rules specify that the influence of the factor/experimental bias is:

- **almost certain** if
  - either more than 4 large experiments support the influence with a similar meaning, no large experiments reject the influence, and less than 2 studies reject the influence;
  - or more than 9 studies support the influence with a similar meaning, and less than 2 studies reject the influence;
  - or the ratio of studies supporting the influence with a similar meaning to studies rejecting the influence is greater than or equal to 10;
- **more likely** if it is not "almost certain" and
  - either more than 2 large experiments support the influence with a similar meaning, and less than 2 studies reject the influence;

  - or more than 6 studies support the influence with a similar meaning, and less than 2 studies reject the influence;
  - or the ratio of studies supporting the influence with a similar meaning to studies rejecting the influence is greater than or equal to 7;
- **somewhat likely** if it is neither "almost certain" nor "more likely" and
  - either more than 2 studies support the influence with a similar meaning, and less than 2 studies reject the influence;
  - or the ratio of studies supporting the influence with a similar meaning to studies rejecting the influence is greater than or equal to 3;
- **inconclusive** if it fits in none of the other categories
- **somewhat unlikely** if it is neither "almost certainly null" nor "less likely" and
  - either more than 2 studies reject the influence, and less than 2 studies support the influence;
  - or the ratio of studies rejecting the influence to studies supporting the influence with a similar meaning is greater than or equal to 3;
- **less likely** if it is not "almost certainly null" and
  - either more than 2 large experiments reject the influence, and less than 2 studies support the influence;
  - or more than 6 studies reject the influence, and less than 2 studies support the influence;
  - or the ratio of studies rejecting the influence on studies supporting the influence with a similar meaning is greater than or equal to 7;
- **almost certainly null** if
  - either more than 4 large experiments reject the influence, no large experiments support the influence, and less than 2 studies support the influence;
  - or more than 9 studies reject the influence, and less than 2 studies support the influence;

– or the ratio of studies rejecting the influence to studies supporting the influence with a similar meaning is greater than or equal to 10.

Table 2.1 summarizes the factors currently used in the discomfort glare metrics; Table 2.2 summarizes the factors related to the context; Table 2.3 summarizes the factors related to the subject; and Table 2.4 summarizes the experimental biases of discomfort glare studies.

Factor	Reference	Subjects	Evaluations	Influence	Direction	Indicator
Luminance of the glare source	[Luckiesh et al. 1949]	50	50	V	A	Almost certain
	[Petherbridge et al. 1950]	6	?	V	A	
	[Einhorn 1969; Einhorn 1979]	R	R	V	A	
	[Hopkinson 1972]	R	R	V	A	
	[Schmidt-Clausen et al. 1974]	10	?	V	A	
	[Chauvel et al. 1982]	R	R	V	A	
	[Waters et al. 1995]	12	288	V	NA	
	[Tokura et al. 1996]	240	2400	V	A	
	[Ngai et al. 2000]	16	1280	V	A	
	[Velds 2000]	84	656	V	A	
	[Dubois 2001]	R	R	V	A	
	[Bullough et al. 2002]	26	468	V	A	
	[Van Derlofske et al. 2004]	31	186	V	A	
	[Mochizuki et al. 2005]	19	114	V	NA	
	[Wienold et al. 2006]	76	349	V	A	
	[Lee et al. 2007a]	42	630	V	A	
	[Tuaycharoen et al. 2007]	168	600	V	NA	
	[Bülow-Hübe 2008]	R	R	V	A	
	[Shi et al. 2008]	21	252	V	A	
	[Eble-Hankins et al. 2009]	67	1608	V	NA	
	[Cai et al. 2012]	?	536	V	NA	
	[Shin et al. 2012]	48	2400	V	A	
	[Clear 2013]	R	R	V	A	
	[Hellinga 2013]	558	S	V	NA	
	[Geerdinck et al. 2014]	42	668	V	NA	
	[Lin et al. 2014]	12	864	V	A	
	[Rodriguez et al. 2014]	25	200	V	A	
	[Carlucci et al. 2015]	R	R	V	A	
	[Chen et al. 2015]	8	576	V	A	
	[Scheir et al. 2015]	R	R	V	NA	
	[Tashiro et al. 2015]	8	?	V	NA	
	[Tyukhova 2015]	47	1692	V	A	
	[Donners et al. 2016]	82	NA	V	NA	
	[Huang et al. 2016]	R	R	V	A	
	[Safdar et al. 2016]	20	2000	V	A	
	[Van Den Wymelenberg et al. 2016]	48	1379	V	A	
	[Huang et al. 2017]	18	324	V	A	
	[Scheir et al. 2017]	20	1440	V	NA	
	[Völker et al. 2017]	R	R	V	A	
	[Yang et al. 2017]	20	3120	V	NA	
Size of the glare source	[Luckiesh et al. 1949]	10	50	V	A	Almost certain
	[Petherbridge et al. 1950]	6	?	V	A	
	[Einhorn 1969; Einhorn 1979]	R	R	V	A	
	[Hopkinson 1972]	R	R	V	A	
	[Chauvel et al. 1982]	R	R	V	A	
	[Boubekri et al. 1992]	40	40	V	A	
	[Tokura et al. 1996]	240	2400	V	A	
	[Velds 2000].	84	656	V	A	
	[Wienold et al. 2006]	76	349	V	A	
	[Aries et al. 2010]	333	S	V	A	
	[Lin et al. 2014]	12	864	V	A	
	[Rodriguez et al. 2014]	25	200	V	A	
	[Tyukhova 2015]	47	1692	V	A	
Position of the glare source	[Hopkinson 1940]	30	?	V	A	Almost certain
	[Luckiesh et al. 1949]	10	270	V	A	
	[Petherbridge et al. 1950]	6	?	V	A	
	[Einhorn 1969; Einhorn 1979]	R	R	V	A	
	[Hopkinson 1972]	R	R	V	A	
	[Schmidt-Clausen et al. 1974]	10	?	V	A	

Factor	Reference	Subjects	Evaluations	Influence	Direction	Indicator
Position of the glare source	[Kim et al. 2005]	25	2400	V	A	Almost certain
	[Chauvel et al. 1982]	R	R	V	A	
	[Iwata et al. 1997]	71	2130	V	A	
	[Bullough et al. 2002]	26	468	V	A	
	[Wienold et al. 2006]	76	349	V	A	
	[Eble-Hankins et al. 2009]	67	1608	V	A	
	[Kim et al. 2009b]	27	1053	V	A	
	[Kim et al. 2010]	32	2144	V	A	
	[Kim et al. 2011]	8	1536	V	A	
	[Lin et al. 2014]	12	864	V	A	
	[Chen et al. 2015]	8	576	V	A	
	[Tyukhova 2015]	47	1692	V	A	
	[Huang et al. 2017]	18	324	V	A	
	[Völker et al. 2017]	R	R	V	A	
Adaptation level	[Hopkinson 1940]	30	?	V	A	Almost certain
	[Luckiesh et al. 1949]	10	30	V	A	
	[Petherbridge et al. 1950]	6	?	V	A	
	[Hopkinson 1957]	R	R	V	A	
	[Hopkinson et al. 1966]	R	R	V	A	
	[Saur 1969]	?	168	X		
	[Hopkinson 1972]	R	R	V	A	
	[Schmidt-Clausen et al. 1974]	10	?	V	A	
	[Einhorn 1979]	R	R	V	A	
	[Chauvel et al. 1982]	R	R	V	A	
	[Iwata et al. 1992b]	46	552	V	A	
	[Tokura et al. 1996]	240	2400	V	A	
	[Ngai et al. 2000]	16	1280	V	A	
	[Fisekis et al. 2003]	10	133	V	A	
	[Kim et al. 2004]	25	375	V	A	
	[Nazzal 2005]	R	R	V	A	
	[Wienold et al. 2006]	76	349	V	A	
	[Sweater-Hickcox et al. 2012]	10	200	V	A	
	[Kim et al. 2012b]	108	4428	V	A	
	[Lin et al. 2014]	12	864	V	A	
	[Völker et al. 2017]	R	R	V	A	
Contrast effect	[Hopkinson et al. 1966]	R	R	V	A	Almost certain
	[Chauvel et al. 1982]	R	R	V	A	
	[Veitch et al. 2000]	94	94	V	A	
	[Wienold et al. 2006]	76	349	V	A	
	[Linney 2008]	48	144	V	A	
	[Osterhaus 2009]	R	R	V	A	
	[Iwata et al. 2011b]	12	108	V	A	
	[Konis 2014]	14	523	V	A	
	[Carlucci et al. 2015]	R	R	V	A	
	[Hansen et al. 2016]	76	428	V	A	
	[Hirning et al. 2017]	341	341	V	A	
Saturation effect	[Bourassa et al. 1966]	3	15	V	A	Almost certain
	[Sivak et al. 1989]	12	1080	V	A	
	[Iwata et al. 1992b]	46	552	V	A	
	[Sivak et al. 1997]	16	1600	V	A	
	[Velds 2000]	84	656	V	A	
	[Wienold et al. 2006]	76	349	V	A	
	[Iwata et al. 2011b]	12	108	V	A	
	[Kim et al. 2012b]	108	4428	V	A	
	[Matusiak 2013]	21	42	V	A	
	[Völker et al. 2017]	R	R	V	A	

Table 2.1: Summary of the factors that have been studied in the literature for their potential influence on discomfort glare perception and currently used in discomfort glare metrics [Pierson et al. 2018b]

Factor	Reference	Subjects	Evaluations	Influence	Direction	Indicator
Spectrum and correlated color temperature	[Hopkinson 1940]	30	?	X		More likely
	[Flannagan et al. 1992]	12	120	V	A	
	[Berman et al. 1995]	12	1080	V	A	
	[Mochizuki et al. 1997]	36	288	V	A	
	[Flannagan 1999]	12	288	V	A	
	[Bullough et al. 2002]	26	468	V	A	
	[Stringham et al. 2003]	3	33	V	A	
	[Van Derlofske et al. 2004]	31	186	V	A	
	[Sivak et al. 2005]	12	540	V	A	
	[Shi et al. 2008]	21	252	X		
	[Bullough 2009]	67	934	V	A	
	[Fekete et al. 2009]	10	2200	V	A	
	[Ishida et al. 2011]	58	1392	V	A	
	[Kimura-Minoda et al. 2011]	15	1395	V	A	
	[Sweater-Hickcox et al. 2012]	10	200	V	A	
	[Akashi et al. 2013]	36	432	V	A	
	[Zhang et al. 2013]	18	180	V	A	
	[Lin et al. 2014]	12	864	V	A	
	[Wei et al. 2014]	26	S	V	A	
	[Chen et al. 2015]	8	576	V	A	
	[Bommel 2015]	R	R	V	A	
	[Yang et al. 2016]	20	960	V	A	
	[Huang et al. 2017]	18	324	V	A	
	[Ko et al. 2017]	176	1760	X		
	[Niedling et al. 2017]	36	648	V	A	
	[Völker et al. 2017]	R	R	V	A	
View direction and position	[Jakubiec et al. 2011]	194	S	V	A	Somewhat likely
	[Hirning et al. 2016]	49	68	V	?	
	[Sarey Khanie et al. 2017]	97	97	V	A	
	[Sekihara et al. 2016]	20	240	V	?	
	[Vásquez et al. 2016]	1	12	V	B	
	[Iwata et al. 2017b]	146	584	X		
	[Völker et al. 2017]	R	R	V	A	
Attractiveness of the view through the window	[Hopkinson 1972]	R	R	V	A	Somewhat likely
	[Chauvel et al. 1982]	R	R	V	?	
	[Osterhaus 2001]	83	S	V	A	
	[Tuaycharoen et al. 2005]	32	1152	V	A	
	[Tuaycharoen et al. 2007]	168	600	V	A	
	[Wienold 2009a]	76	349	V	A	
	[Tuaycharoen 2011]	76	752	V	A	
	[Shin et al. 2012]	48	2400	V	A	
	[Hellinga 2013]	558	S	X		
	[Matusiak 2013]	21	42	V	A	
	[Hirning et al. 2014]	468	493	X		
	[Kent 2016]	40	720	V	A	
	[Iwata et al. 2017b]	146	584	X		
Air temperature	[Mochizuki et al. 1998]	10	540	V	A	Inconclusive
	[Laurentin et al. 2000]	20	180	X		
	[Yamin Garretón et al. 2015]	19	57	V	A	
Noise	[Mochizuki et al. 1998]	10	540	V	A	Inconclusive
Time of the day	[Borisuit et al. 2015]	25	400	X		Somewhat likely
	[Kent et al. 2015a]	30	480	V	A	
	[Altomonte et al. 2016a]	20	960	V	A	
	[Kent et al. 2017a]	40	720	V	A	
Season	[Ishida et al. 2011]	58	1392	X		Inconclusive
	[Van Den Wymelenberg 2012b]	93	1488	V	A	

Factor	Reference	Subjects	Evaluations	Influence	Direction	Indicator
Task difficulty	[Sivak et al. 1989]	12	1080	V	A	Somewhat likely
	[Flannagan et al. 1990]	24	4320	V	A	
	[Osterhaus et al. 1992]	26	?	V	B	
	[Altomonte et al. 2016a]	20	960	V	A	
	[Völker et al. 2017]	R	R	V	?	
	[Kent et al. 2018b]	24	480	V	B	
Duration of exposure	[Hopkinson 1957]	3	?	V	A	Inconclusive
	[Iwata et al. 1990]	80	800	V	A	
	[Sivak et al. 1997]	16	1600	V	B	
	[Mochizuki et al. 1998]	10	540	V	A	
	[Inoue et al. 1989]	3	1944	V	A	
	[Logadóttir et al. 2011]	36	1296	X		
	[Geerdinck 2012]	42	840	X		
	[Logadóttir et al. 2013]	36	864	V	NA	
	[Kent et al. 2017c]	R	R	V	A	

Table 2.2: Summary of the factors that have been studied in the literature for their potential influence on discomfort glare perception and related to the context [Pierson et al. 2018b]

Factor	Reference	Subjects	Evaluations	Influence	Direction	Indicator
Gender	[Saur 1969]	35	70	X		Almost certainly null
	[Sivak et al. 1989]	12	1080	X		
	[Iwata et al. 1992a]	40	480	X		
	[Pulpitlova et al. 1993]	57	456	X		
	[Tuaycharoen et al. 2007]	168	600	X		
	[Shin et al. 2012]	48	2400	X		
	[Kent et al. 2015a]	30	480	X		
Age	[Saur 1969]	35	70	X		Inconclusive
	[Bennett 1977]	199	1393	V	A	
	[Olson et al. 1984]	40	7200	V	A	
	[Vos et al. 1995]	400	S	X		
	[Mochizuki et al. 1997]	50	750	V	B	
	[Iwata et al. 1997]	71	2130	V	A	
	[Flannagan 1999]	12	288	V	A	
	[Osterhaus 2001]	83	S	X		
	[Shi et al. 2008]	21	252	X		
	[Shin et al. 2012]	48	2400	X		
	[Van Den Wymelenberg 2012b]	93	1488	X		
	[Akashi et al. 2013]	36	432	V	B	
	[Hirning et al. 2014]	468	493	X		
	[Kuhn et al. 2013]	45	270	V	A	
	[Wolska et al. 2014]	50	100	V	B	
	[Kent et al. 2015c]	30	480	X		
	[Akashi et al. 2017]	24	192	V	C	
	[Facchin et al. 2017]	50	4950	V	B	
	[Völker et al. 2017]	R	R	V	A	
Socio-environmental context	[Ichikawa et al. 1964]	15	15	V	A	Somewhat likely
	[Luckiesh et al. 1949]	50	50			
	[Subova et al. 1991]	32	256	V	B	
	[MacGowan et al. 1988]	?	?			
	[Iwata et al. 1992a]	40	480			
	[Petherbridge et al. 1950]	6	?	V	A	
	[Hopkinson 1971]	?	?			
	[Pulpitlova et al. 1993]	57	456			
	[MacGowan et al. 1986]	?	?	V	A	
	[Iwata et al. 1992a]	40	480			
	[Iwata et al. 1998b]	40	400	V	A	
	[Tokura et al. 1996]	240	2400			
	[Lee et al. 2007b]	42	630	V	A	
	[Hopkinson 1971]	?	?			
	[Kent et al. 2015b]	30	480	X		
	[Ko et al. 2017]	176	1760	V	A	
	[Mangkuto et al. 2017]	86	86	V	C	
	[Wienold et al. 2006]	76	349			
	[Iwata 2018]	54	216	X		
Chronotype	[Kent et al. 2015a]	30	480	V	A	Inconclusive
Glare sensitivity	[Saur 1969]	35	70	V	A	Inconclusive
	[Osterhaus 2001]	83	S	V	A	
	[Inkarojrit 2005]	25	83	X		
	[Rodriguez et al. 2014]	25	200	V	A	
	[Kent et al. 2015a]	30	480	X		
	[Rodriguez et al. 2016b]	32	64	X		
Visual acuity	[Saur 1969]	35	70	X		Almost certainly null
	[Iwata et al. 1992a]	40	480	X		
	[Iwata et al. 1997]	71	2130	X		
	[Sivak et al. 1997]	16	1600	X		
	[Tuaycharoen et al. 2007]	168	600	X		
	[Shin et al. 2012]	48	2400	X		
	[Hirning et al. 2014]	468	493	X		

Factor	Reference	Subjects	Evaluations	Influence	Direction	Indicator
Contrast sensitivity	[Eble-Hankins 2008]	67	1608	V	A	Inconclusive
Iris pigmentation	[Saur 1969]	35	70	X		Inconclusive
	[Bennett 1977]	199	1393	V	A	
	[Iwata et al. 1998b]	40	400	X		
	[Osterhaus 2001]	83	S	V	A	
	[Stringham et al. 2011]	26	468	X		
	[Rodriguez et al. 2016b]	32	64	X		
Macular pigment optical density	[Stringham et al. 2004]	4	O	V	A	Somewhat likely
	[Loughman et al. 2010]	142	O	X		
	[Lien et al. 2011]	R	R	V	A	
	[Stringham et al. 2011]	26	468	V	A	
Cortical hyperexcitability	[Bargary et al. 2015]	28	280+O	V	A	Inconclusive
Previous luminous environment	[Bennett 1977]	199	1393	V	A	Inconclusive
	[Inoue et al. 1989]	3	1944	V	B	
	[Iwata et al. 1992b]	46	552	X		
	[Pulpitlova et al. 1993]	57	456	V	?	
	[Kent et al. 2015a]	30	480	V	C	
	[Altomonte et al. 2016a]	20	960	V	D	
Physical state	[Osterhaus 2001]	83	S	X		Inconclusive
Emotional state	[Osterhaus 2001]	83	S	X		Inconclusive
	[Altomonte et al. 2016a]	20	960	V	A	
Caffeine ingestion	[Kent et al. 2015a]	30	480	V	A	Somewhat likely
	[Altomonte et al. 2016a]	20	960	V	A	
Food ingestion	[Kent et al. 2015a]	30	480	X		Somewhat unlikely
	[Altomonte et al. 2016a]	20	960	X		
Fatigue	[Kent et al. 2015a]	30	480	V	A	Somewhat likely
	[Altomonte et al. 2016a]	20	960	V	A	

Table 2.3: Summary of the factors that have been studied in the literature for their potential influence on discomfort glare perception and related to the subject [Pierson et al. 2018b]

Experimental bias	Reference	Subjects	Evaluations	Influence	Direction	Indicator
Glare rating scales	[Rea 1982]	6	36	V	A	Somewhat likely
	[Olson et al. 1984]	13	2600	V	NA	
	[Gellatly et al. 1990]	26	?	V	A	
	[Geerdinck 2012]	42	840	V	NA	
	[Van Den Wymelenberg 2014]	R	R	V	A	
	[Fotios 2015]	R	R	V	A	
	[Kent et al. 2017c]	R	R	V	A	
Anchor bias	[Osterhaus et al. 1992]	26	?	V	A	Somewhat likely
	[Fotios et al. 2010]	21	126	V	NA	
	[Fotios et al. 2011]	R	R	V	NA	
	[Logadóttir et al. 2011]	36	1296	V	NA	
	[Logadóttir et al. 2013]	36	864	V	NA	
	[Uttley 2019]	40	320	V	NA	
	[Kent et al. 2017c]	R	R	V	A	
	[Kent et al. 2017b]	22	352	V	A	
Order bias	[Kent et al. 2017c]	R	R	V	A	Somewhat likely
	[Kent et al. 2018c]	20	240	V	A	
	[Kent et al. 2018a]	55	880	V	A	
Stimulus range bias	[Lulla et al. 1981]	20	360	V	A	Somewhat likely
	[Olson et al. 1984]	40	7200	V	A	
	[Fotios et al. 2010]	21	126	V	NA	
	[Fotios et al. 2011]	R	R	V	NA	
	[Logadóttir et al. 2011]	36	1296	V	NA	
	[Logadóttir et al. 2013]	36	864	V	NA	
	[Geerdinck et al. 2014]	42	668	V	NA	
	[Kent et al. 2017c]	R	R	V	A	
	[Kent et al. 2019]	42	1092	V	A	
Study type	[Olson et al. 1984]	40	7200	V	A	Inconclusive
	[Völker et al. 2017]	R	R	V	A	

Table 2.4: Summary of the experimental biases that have been studied in the literature for their potential influence on the results of discomfort glare studies [Pierson et al. 2018b]

2.4.2 Research Gaps

This chapter has reviewed the state of the art related to discomfort glare perception from daylight. A description of discomfort glare perception and a brief history of the metrics developed to evaluate it have been given. Since it has been shown that these metrics cannot consistently and accurately evaluate discomfort glare perception from daylight, other variables than those currently used might play a role in the perception of discomfort glare from daylight. Therefore, all the factors having already been studied for their potential influence on discomfort glare perception have been discussed, as well as some potential experimental biases.

The likelihood (or unlikelihood) of the influence of these factors and experimental biases is categorized by an indicator based on the number of studies having investigated the factor, the sample size of these studies, and the agreement between them. The indicator categories classify the influence of a factor or experimental bias as "almost certain", "more likely", "somewhat likely", "inconclusive", "somewhat unlikely", "less likely", or "almost certainly null". The magnitude of each influence can, however, not be determined from the data available in the literature.

From Tables 2.1 to 2.4, it can be observed that the six factors currently used in discomfort glare metrics have been tested numerous times, and have therefore an almost certain influence on discomfort glare perception. Since it has been demonstrated that discomfort glare can be due to two main effects, the saturation and the contrast glare, both effects should be taken into account in discomfort glare models in the future.

Conversely, some factors that have also been studied numerous times (the gender and the visual acuity of the subject) have almost certainly no influence on discomfort glare perception. Another factor (food ingestion) should not have any influence, even though additional studies are required to confirm it.

On another note, it can likewise be seen that a large number of factors are expected to be influencing discomfort glare perception. Among these factors, one, i.e., the spectrum and CCT, would just

need one or two large studies to validate its influence, while others (view direction and position, attractiveness of the view through the window, time of the day, task difficulty, socio-environmental context, MPOD, caffeine ingestion, and fatigue) still need considerable investigation before drawing any conclusion on their influence on discomfort glare perception. Most of the experimental biases (glare rating scales, anchor bias, order bias, and stimulus range bias) are also likely to influence the results of discomfort glare studies, even though further research is required.

The literature was inconclusive on the influence on discomfort glare perception of a large number of factors (air temperature, noise, season, duration of exposure, age, chronotype, glare sensitivity, contrast sensitivity, iris pigmentation, cortical hyperexcitability, previous luminous environment, physical state, and the emotional state of the subject). As can be observed from the tables, for some of these factors, the uncertainty is due to the fact that the influence is highly debated among researchers, but for most of them, the uncertainty is due to the lack of studies having investigated their influence.

In addition, caution should be taken as some factors might interact. For instance, fatigue and time of the day are two factors closely linked. Therefore, the correlation found between fatigue and perceived discomfort glare should not be directly related to the influence of fatigue since the time of the day could also have played a role. The self-assessed glare sensitivity and the cortical hyperexcitability also seem to be related. For that reason, more research is necessary to clarify the influence of these factors.

What can be learned from this literature review is that more research is needed to explain the large variation between subjects' discomfort glare perception, but also more research is required to design better discomfort glare studies and produce reliable results. The influence indicator developed here can help in defining a research agenda, to define which factors should be studied in priority and to what extent.

The first efforts should be directed towards factors classified as more

or somewhat likely, as these factors are our best chances to better predict discomfort glare perception.

For instance, a large experiment should be conducted on the perception of discomfort glare from filtered daylight to confirm the influence of the spectrum of light on discomfort glare perception. This will be very useful as new glazing types, such as electrochromic windows, are currently being developed. One or two large experiments should also aim at clarifying the influence of the view through the window and its attractiveness on discomfort glare perception from daylight. Indeed, this factor was believed to considerably influence discomfort glare perception due to the results of several laboratory experiments mainly using simulated windows. However, recent field studies have challenged this assumption as the effect could not be observed in the results with real window views. Therefore, the hypothesis that, when the view implies no strong attraction or revulsion, its influence on discomfort glare perception is somehow largely reduced, should be tested.

Moreover, since the goal is to better predict the large variation between subjects' discomfort glare perception, and since discomfort glare up to now is evaluated through subjective assessments, the factors related to the subject should be considered as a priority.

In particular, the socio-environmental context of the subject would be a very pertinent factor to study. Indeed, the socio-environmental context of the subject is one of the only factors that has never been investigated by a dedicated study, i.e., no study has had its protocol defined to test the influence of the socio-environmental context on discomfort glare perception. However, the uncertainty of its influence is a real issue in discomfort glare research today, and this factor is increasingly mentioned as limiting in discomfort glare studies [Rodriguez et al. 2016a; Mangkuto et al. 2018; Jakubiec et al. 2018]. There is therefore a necessity to investigate whether the somewhat likely influence of the socio-environmental context is supported by the results of a dedicated study.

In parallel, each discomfort glare study in the future should ensure that as few experimental biases as possible, particularly from those

listed here, affect its results. If priority is not given to addressing these potential experimental biases, a large part of the upcoming research effort might be wasted.

Secondly, it might be interesting to study the influence of food ingestion, the only factor classified as less likely or somewhat unlikely, on discomfort glare perception in one or two additional studies. By doing so, this factor could be potentially ruled out from the list, together with the visual acuity and the gender of the subject.

Finally, the numerous factors having an inconclusive influence should be examined. In the first place, all the inconclusive factors of which the influence on discomfort glare perception has only been tested in one, two, or three studies should be further investigated. One large experiment testing these factors might indeed be enough to have a better idea of its potential influence on discomfort glare perception. After more insight is gained on these factors, the more controversial inconclusive factors should be further studied. If a factor has been studied several times and its influence remains inconclusive, it is expected that either the influence of the factor is very small and maybe not significant, or the method used to study the factor is not adequate.

Chapter 3

Research Aim

3.1 General Hypothesis

In the previous Chapter, the state of the art related to discomfort glare perception from daylight is reviewed. The metrics that have been developed to evaluate discomfort glare perception from daylight are presented in a chronological order and detailed. Since these metrics are observed not to provide consistent and accurate predictions of discomfort glare from daylight, other factors potentially influencing discomfort glare perception are listed and discussed. Potential experimental biases are also reviewed as these could influence the results of discomfort glare studies and affect our understanding of discomfort glare perception.

By summarizing the learning from the state of the art, several research gaps in the field of daylight discomfort glare research are identified. These gaps are related to the incertitude of the influence of some factors on discomfort glare perception, as well as to the potential effect of some experimental biases. As has already been rightly said by Van Den Wymelenberg [Van Den Wymelenberg 2014], one of the current glare knowledge gaps is the effect of moderating variables such as the view through the window, the CCT of light, or the socio-environmental context.

On the basis of these research gaps, the following general hypothesis is made:

The prediction of discomfort glare perception from daylight in office buildings can be improved by including relevant additional factors related to the context or to the subject in the models.

In other words, the large variation between subjects' discomfort glare perception, as well as the inconsistency of the metrics in different studies, could be substantially explained by taking into account the influence of additional factors related to the context or to the subject on discomfort glare perception from daylight.

This hypothesis, based on which the research questions will be developed, is deliberately delimited by two elements: discomfort glare

perception **from daylight**, and discomfort glare perception **in office buildings**.

On the one hand, improving energy performance and occupants' well-being is the ambition of this research. Daylight was shown in Section 1.1 to be more valuable than electric light for that purpose. Moreover, as discomfort glare sources from daylight do not operate in the exact same manner as discomfort glare sources from electric light (Subsection 2.1.3), it is preferable to study them separately so as not to make the topic more complex than it already is.

On the other hand, people nowadays spend 90% of their time indoors on average [Klepeis et al. 2001; WHO 2014], and a large part of it is spent at their office during the daylight hours. If there is one place where daylight integration should be optimized, it is where subjects spend most of their time.

Improving the prediction of discomfort glare perception from daylight in office buildings seems therefore the most relevant aim in this field in view of the lifestyle and needs of "level 4" societies [Rosling et al. 2018].

3.2 Research Questions

The general hypothesis of this research states that the prediction of discomfort glare perception can be improved by including other relevant factors in the models. These other relevant factors are those, in the list of 31 factors (minus the six currently used in discomfort glare metrics) established in the state of the art (Section 2.2), which have a somewhat or more likely influence on discomfort glare perception.

However, the influence of the eight factors classified as "somewhat likely" or "more likely" in Tables 2.2 and 2.3 cannot be studied in the framework of this research. The dataset required to study such a large number of variables can hardly be collected by one investigator. Moreover, specific equipment is needed to record some of these factors, such as the MPOD, which was not available.

Therefore, the influence of only one specific factor will be thoroughly studied in this research: **the socio-environmental context of the subject**. There are several reasons for this choice:

- The socio-environmental context factor has been identified as having a somewhat likely influence on discomfort glare perception from daylight in the literature review.
- Most of the studies having suggested an influence of the socio-environmental context on discomfort glare perception have drawn their conclusion based on the comparison of their results with other studies. Very few studies have actually tested the difference in discomfort glare perception between different socio-environmental groups according to a unique protocol.
- If the socio-environmental context factor is demonstrated to significantly influence discomfort glare perception, the metrics could be independently adapted for each socio-environmental context.
- The daylight discomfort glare metrics are principally developed to assist decision makers during the building design phase. For this purpose, the implementation of the socio-environmental factor in the metrics is much more relevant than the im-

plementation of another subjective factor, such as self-assessed glare sensitivity for instance. Since a building is located in a specific socio-environmental context, the socio-environmental factor can help produce more accurate prediction of discomfort glare perception for all occupants of the building, whereas these occupants most probably have very different self-assessed glare sensitivities.

- The perception of other environmental elements has already been shown to be influenced by the subject's socio-environmental context. For instance, thermal comfort [Hirashima et al. 2018; Kenawy et al. 2013; Aljawabra et al. 2018; Knez et al. 2006], visual perception [Segall et al. 1968; Ishii et al. 2009], or lighting preferences [Belcher 1985; Park et al. 2010; Kim et al. 2016; Ko et al. 2017] vary between subjects of different socio-environmental contexts.

Consequently, the main research question that the study will try to answer is:

Main Research Question

Does the socio-environmental context of a subject influence her/his discomfort glare perception from daylight in office buildings?

As defined in Subsection 2.2.3 (p.114), the socio-environmental context of the subject refers to the climate and habitat, including indoors and outdoors, to which a subject has been acclimatized, her/his behavior towards these elements, and her/his expectations about them. The literature suggests that discomfort glare perception is influenced by the socio-environmental context of the subject (Subsection 2.2.3). More specifically, Asian subjects seem less sensitive to discomfort glare than North American ones, who, in turn, seem less sensitive than European subjects. Therefore, the nature of the main research question is **explanatory research**. It consists in testing a hypothesis that specifies the nature of the relationship between variables, i.e. the socio-environmental context and discom-

fort glare perception. The protocol of the study is established to answer this main research question.

Nevertheless, several other research gaps have been identified in the state of the art (Section 2.4). In order to provide further insight about these research gaps, two additional, but secondary, research questions are defined. Indeed, besides the six factors currently used in the metrics and the socio-environmental context, 24 other factors have been listed as factors potentially influencing discomfort glare perception. Many of these factors could also help explain the large variation of subjects' discomfort glare perception. Since data already needs to be collected for the main research question, several additional factors could be investigated at the same time. Thirteen potential additional factors from Tables 2.1, 2.2, and 2.3 are therefore selected to be further studied, being easily measurable without requiring too much additional effort.

Of the 11 factors that will not be further studied, eight are excluded for the reasons that it is not clear how to measure them correctly, that their measurement requires specific equipment or a long time, or that it is not possible to collect a balanced dataset. These eight rejected factors are: spectrum and CCT of light, view direction and position, noise, MPOD, cortical hyperexcitability, contrast sensitivity, previous luminous environment, and food ingestion.

Moreover, the season factor is also excluded for two reasons. Firstly, comparable lighting situations that maximize the occurrence of discomfort glare from daylight are needed. These conditions are hardly achievable when conducting a study both in summer and winter. Secondly, not to confound the potential influence of season with that of socio-environmental context, an equal proportion of data collected in each season should be found in each socio-environmental context. This condition implies that data should be collected in different seasons in each context, requiring several trips of the investigator in the studied contexts, which was logistically not possible without removing at least one context.

Finally, the task difficulty and the duration of exposure factors are also excluded, as the collection of data needed to look at these fac-

tors might endanger the investigation of the main research question. These two factors would indeed require a modification of the protocol of the study between subjects, since the difficulty of the task performed by the subject and the time during which the subject is exposed to discomfort glare from daylight would need to be varied. Since the priority is set on answering the main research question, the protocol of the study should not be modified to examine the influence of another factor than the socio-environmental context.

Consequently, the first additional research question is:

Additional Research Question 1

Do any of the factors from the list below have a probable influence on the subject's discomfort glare perception from daylight in office buildings?

- the gender of the subject
- the age of the subject
- the chronotype of the subject
- the glare sensitivity of the subject
- the visual acuity of the subject
- the iris pigmentation of the subject
- the physical state of the subject
- the emotional state of the subject
- the fatigue of the subject
- the caffeine ingestion of the subject
- the attractiveness of the view through the window
- the air temperature
- the time of the day

Depending on the available data and whether a representative sample of the population is collected, the influence of these potential additional factors on discomfort glare perception from daylight can

be tested. However, since the study is not designed for that purpose, the results of these tests cannot be used to determine the influence of the factors. The aim is rather to suggest which factors from the list of 13 might have higher probabilities of influencing discomfort glare perception from daylight. The nature of this first additional research question is therefore **exploratory research**, as it seeks to create hypotheses for future studies.

In addition, the influence that the study (and its methodology) could have on the results should not be ignored. Experimental biases, which would not have an impact if discomfort glare perception would not be studied, could influence the way discomfort glare is perceived or reported by the subjects, or how it is understood by the researchers. Although only five potential experimental biases of discomfort glare studies have been reported in the literature (Section 2.3), these biases can be multiple and related to different parts of the protocol, such as the subjective assessment method, the lighting measurement method, the statistical analyses, or the study type. To ensure that the results of studies on discomfort glare perception are reliable and can be used to develop our knowledge in this field, the experimental biases should be identified and avoided.

Consequently, a second additional research question is:

Additional Research Question 2

Do any of the experimental biases from the list below have a probable influence on the results of studies on discomfort glare perception?

- glare rating scales
- the study type
- the anchor bias
- the order bias
- the stimulus range bias

Since experimental biases are directly related to the protocol of the study, they cannot be recorded per se, and their influence cannot be investigated as it is done for the 13 other additional factors. Instead, external datasets, comparison with published studies, and descriptive analyses will be used to further investigate some of these experimental biases in the framework of this study.

Similarly to the first additional research question, the aim is to inform on some experimental biases that might influence the results of studies on discomfort glare perception. The nature of this second additional research question is therefore also **exploratory research**, as it does not seek to test the influence of a specific experimental bias but rather to draw attention to some of them.

In conclusion, the data collected through the study, of which the methodology is described in Chapter 4, will be used to answer the three research questions, although the priority is set on the main one. The study is therefore designed primarily to answer the main research question. The results regarding the three research questions are explained respectively in Chapters 6, 7, and 8.

Chapter 4

Methodology

4.1 Study Design

As stated in Chapter 3, the main question this research is trying to answer is whether the socio-environmental context of a subject influences her/his discomfort glare perception from daylight in office buildings.

For this purpose, a study was designed and conducted according to the methodology presented in this chapter.

This section describes the protocol that has been applied to collect the data. The data processing steps are detailed in Section 4.2. The rules applied to cleanse the data are defined in Section 4.3. The final dataset is summarized in Section 4.4, and the statistical methods that will be used to analyze it are described in Section 4.5.

4.1.1 Study Type

The main research question of the study requires to evaluate the relationship between the socio-environmental context of the subject (the independent variable), and her/his discomfort glare perception from daylight (the dependent variable). For this purpose, discomfort glare perceptions from subjects of different socio-environmental contexts have to be collected and compared.

However, the socio-environmental context of a subject, as described in Subsection 2.2.3, is a variable which is very difficult to manipulate or control. Since it takes a person around two years of living in a specific socio-environmental context to be acclimatized to it, the investigator could not assign at random subjects into different groups. The uncontrollability of the socio-environmental context variable had two main implications on the study design:

1. An observational study had to be conducted instead of an experimental study.
2. A between-subjects design had to be adopted rather than a within-subjects design.

Unlike an experimental study in which an investigator manipulates the variable of interest and observes the effect, an observational

study requires the investigator to observe what happens in the real world without interfering with it. Furthermore, a between-subjects or between-groups design uses separate groups of subjects for each of the different conditions in the experiment, conversely to a within-subjects or repeated-measures design [Andy Field 2002]. The two implications related to the uncontrollability of the socio-environmental context variable are linked since the central issue for the two design choices (observational/experimental and between/within) comes down to choose whether to examine effects within the same subjects or across different subjects [Miller 2017].

Of the three types of observational studies, namely longitudinal, case-control, or cross-sectional studies, the cross-sectional study was the one required for this research. The cross-sectional study consists in taking a snapshot of the variable of interest —i.e., discomfort glare perception in this study— at a point in time [Field 2016], for subjects naturally occurring in different groups —i.e., different socio-environmental context in this study— [Everitt 2011]. On another note, a longitudinal study requires to study subjects of different groups for a period of time and observe the evolution of the variable of interest, whereas in a case-control study, subjects differing in their outcome of the variable of interest are compared.

In practical terms, the implementation of a cross-sectional, between-subjects study meant that, to test the influence of socio-environmental context on discomfort glare perception from daylight, point-in-time discomfort glare evaluations would have to be collected for different subjects of different socio-environmental contexts, namely subjects living in different parts of the world. The influence of the socio-environmental context on discomfort glare perception would then be investigated by comparing discomfort glare evaluations between each socio-environmental group.

The environment in which the point-in-time discomfort glare evaluations would be collected also had to be defined. This environment obviously had to be an office with a window for daylight, but it could either be an office-like laboratory cell, or a real office in the field. Despite the fact that laboratory studies offer the most appro-

priate way for drawing causal conclusions due to the large control on extraneous variables, a field study was chosen for several reasons:

- the difficulty to recreate the same office-like environment in different parts of the world

  In order not to include bias between the socio-environmental groups, the simulated environment had to be the same in each socio-environmental context. Building a similar office-like laboratory cell in different parts of the world, or moving a demountable one, was outside the budget. Using existing office-like laboratory cells were also considered prohibitive because of the difficulty to find similar ones in different parts of the world, and because of their reduced accessibility to external researchers.

- the ambition to avoid subjective assessments biased by an unfamiliar environment

  Office environments might differ around the world, making the definition of a universal setting of an office-like laboratory cell difficult. An office-like setting not representative of usual offices in one of the socio-environmental contexts might have biased the behaviors and perceptions of the subjects from that context.

- the necessity to limit the organizational load

  As previously mentioned, discomfort glare evaluations would have to be collected from subjects of different parts of the world. The time spent by the investigator in each testing location would be allotted only to the collection of these evaluations. Therefore the organization of the study would have to be executed remotely in advance. For this reason and to reduce organizational complications during the study, the organizational load had to be restricted. A field study in which the subjects are observed in their real working environment seemed appropriate, as it did not require to arrange in advance for the subjects to come to the laboratory cell and to compensate for their trip.

It was decided that the study would take place directly in the sub-

jects' offices, and in situ discomfort glare evaluations would be collected, even though this decision would result in more noisy data.

To study the influence of the socio-environmental context on discomfort glare perception, discomfort glare perceptions have to be evaluated and compared between different contexts. A psychophysical study is required to evaluate discomfort glare perception, namely a study that looks at the relation between a stimulus and a sensation [Van Den Wymelenberg 2012b]. Both the subjective assessment of discomfort glare, collected from the subject via glare rating scales in a questionnaire for example (Subsection 4.1.5), and its physical measurement, measured through the discomfort glare metrics, are needed in each socio-environmental context, unless the stimulus is fixed throughout the study.

When working with daylight, however, a stimulus can never be fixed, since daylight is dynamic and cannot be controlled. Furthermore, compared to laboratory studies, very diverse visual scenes occur in field studies. In order to compare point-in-time subjective assessments of discomfort glare from daylight, the visual scenes, and more specifically the discomfort glare stimuli in the scenes, have to be measured and taken into account in the analyses to ensure a fair basis of comparison. Hence the necessity to collect both the measurement and the subjective assessment of the visual scene for each discomfort glare evaluation.

To discern the feasible options to evaluate discomfort glare from daylight in real office environments, a literature review of field studies looking at discomfort glare perception from daylight at the subjects' office desk was performed. Only three relevant studies [Hirning et al. 2014; Konis 2014; Painter et al. 2009] were found at that time, and are summarized in Table 4.1.

Ideally, the measurement and subjective assessment of the visual scene should be made at the exact same location and time, as daylight is spatially and temporally dependent. To this end, the first idea was to mount a novel small vision sensor [Motamed et al. 2015] on glasses that the subjects would have to wear while making the subjective assessment. By allowing real time capturing of lumi-

Study	Study design	Number of subjects	Number of evaluations	Study timing	Discomfort glare evaluation	Lighting conditions
[Hirning et al. 2014]	Almost between-subjects	468	493	Cross-sectional study: subjects observed at one point in time, one after the other	Subjective assessment of discomfort glare just before measurement of discomfort glare	Stable: clear skies and electric lighting on
[Konis 2014]	Within-subjects	14	523	Longitudinal study: subjects observed simultaneously during two weeks	Measurement of discomfort glare simultaneously to subjective assessment of discomfort glare	Stable: clear skies and electric lighting on
[Painter et al. 2009]	Within-subjects	6	4797	Longitudinal study: subjects observed simultaneously during one year	Measurement of discomfort glare simultaneously to subjective assessment of discomfort glare	Changing: clear to fully overcast skies and electric lighting potentially on

Table 4.1: Summary of the study design of three recent field studies looking at discomfort glare perception from daylighting

nance maps of visual scenes, the sensor could have measured the discomfort glare stimulus as seen by the subject while he/she would have been assessing it. However, this idea did not prove feasible since the sensor was not ready for use (validation tests missing) at the start of the study.

Therefore, another technique to measure the visual scene and the discomfort glare stimulus, similar to the technique used in the three studies of Table 4.1, was adopted. The technique, called High Dynamic Range (HDR) photography, is described in detail in Subsection 4.1.7. This technique requires the use of equipment that could not be mounted on glasses. As a consequence, the subjective assessment and the measurement of the visual scene could not be made at the same location and time.

A similar location was preferred to a similar time, even though it required the lighting conditions to be stable. The measurement of the visual scene was thus collected directly after the subjective assessment, at the exact same location. The reason for this decision was that the error related to a position offset of the HDR measuring equipment from a subject's point of view has already been studied, and the displacement of the equipment has been acknowledged to influence the accuracy of the measurements [Fan et al. 2009]. The setup of the measuring equipment is explained in Subsection 4.1.8.

Besides the discomfort glare evaluations from different socio-environmental contexts, additional data were collected during the study. Thirteen factors, which are the focus of one of the additional research questions, were recorded either via the questionnaire (Subsection 4.1.6) or by measurements (Subsection 4.1.7), depending on the factor. The experimental biases, which are the focus of the second additional research question, are studied separately and do not require to be recorded. Since the main research question concerns the socio-environmental context, no efforts were made to have a dataset evenly distributed among the groups of a categorical variable, or along the scale of a continuous variable in these additional factors.

In summary, a cross-sectional, between-subjects study was con-

ducted in real office buildings located in several socio-environmental contexts around the world. The chosen socio-environmental contexts and the number of subjects are detailed respectively in Subsections 4.1.2 and 4.1.3. A discomfort glare evaluation was collected at the office desk of each subject having a certain type of visual scene, as described in Subsection 4.1.4, together with the evaluation of 13 additional factors. Three types of measures were therefore collected during the study:

- measures of the subject's response to the visual environment, i.e., the subjective glare assessments, via questionnaire (Subsection 4.1.5)
- measures of the subject's profile, including the physiological and psychological additional factors, via questionnaire (Subsection 4.1.6)
- measures of the environment, including the measurement of the visual scene, via HDR photography and other sensors (Subsection 4.1.7)

The setup of the equipment to collect these measures is described in Subsection 4.1.8. Finally, the pilot study conducted to validate the protocol is described in Subsection 4.1.9, and the final procedure is detailed in Subsection 4.1.10.

4.1.2 Socio-Environmental Contexts

To study the difference in discomfort glare perception between subjects from different socio-environmental contexts, which has been defined in Subsection 2.2.3 (p.114), discomfort glare evaluations had to be collected in several socio-environmental contexts. As previously discussed (Subsection 2.2.3), the socio-environmental context is defined here as **the climate and habitat, including indoors and outdoors, to which a subject has been acclimatized, her/his behavior toward these elements, and her/his expectations about them**. Different socio-environmental contexts can therefore be found all around the world.

However, finding people from different socio-environmental con-

texts in the same location proved to be unachievable, especially because people acclimatized to their surrounding context after a certain period of time. The subjects therefore had to be recruited directly from different locations, and the investigator had to travel to these locations to conduct the study. Having the same investigator conducting the study in every location ensured that the same protocol and the same equipment were used for each socio-environmental context. For practical and budgetary reasons, the study could be conducted in three (or four depending on the location) different socio-environmental contexts, thus three or four locations around the world.

To avoid any ambiguities, it was decided that three very different socio-environmental contexts would be selected. Hence three cities where office buildings could be found, from different continents, with different climates and different cultures, had to be chosen.

In the literature, several studies suggested a difference in discomfort glare perception between European and Asian populations [Iwata et al. 1992a; Pulpitlova et al. 1993; Lee et al. 2007b; Huang et al. 2016; Ko et al. 2017]. The first two cities would therefore be from Europe and Asia. Louvain-la-Neuve (Belgium) was chosen as the European city since the investigator was established there. Regarding the Asian city, Tokyo (Japan) was chosen given the local presence of Prof. Iwata and her team in daylighting research, and given that Prof. Iwata was one of the first researchers to suggest that the socio-environmental context could influence discomfort glare perception.

The third city was chosen so that it was located on a different continent than that of the first two cities, and preferably in South America for its tendency towards sunny climates and its Latino culture. Chile was selected given the local presence of Dr. Piderit, with whom collaborations with the Belgian laboratory were ongoing. However, not one but three cities were selected in Chile. The reason for this was to also compare these three cities to each other if enough discomfort glare evaluations could be collected in each city. However, the sample size proved to be too small for this internal comparison, and the data from the three Chilean cities were

analyzed as one socio-environmental context.

At a later stage, Lausanne (Switzerland) was added as a fourth city, and thus a fourth socio-environmental context. The reason for this was that if the discomfort glare perception of three significantly different socio-environmental contexts (CL, BE, JP) was found to be different, it would be interesting to know whether this observation holds for two slightly different socio-environmental contexts (BE, CH). Moreover, findings in the PhD research of Dr. Cauwerts [Cauwerts 2013], which were a strong motivator for this research topic, suggested that there was a variation in the glare tolerance of subjects from two slightly different socio-environmental contexts, i.e. Louvain-la-Neuve (Belgium) and Lyon (France).

In summary, the four locations selected for their socio-environmental contexts are located in Figure 4.1, and listed in chronological order of study:

- Cities in Chile, referred to collectively as CL:
  - Concepción (36°49′12″S 73°2′40″W)
  - Punta Arenas (53°9′17″S 70°54′41″W)
  - Antofagasta (23°38′60″S 70°24′0″W)
- Louvain-la-Neuve (50°40′12″N 4°36′36″E) in Belgium, referred to as BE
- Tokyo (35°39′10″N 139°50′22″E) in Japan, referred to as JP
- Lausanne (46°31′12″N 6°38′1″E) in Switzerland, referred to as CH

The daylight availability of these four socio-environmental contexts was compared through the averaged annual sum of Global Horizontal Irradiance (GHI) to compare outdoor lighting levels. The GHI is the total irradiance from the sun, including both direct and diffuse irradiance, on a horizontal surface on Earth [Reno et al. 2012].

In Figure 4.2, the yearly sum of GHI per location is given, which has been averaged from data collected over a period of 9 to 21 years depending on the location [Solargis 2010]. Chile offers the highest annual sum of GHI, with around 2200 kWh/m^2 in Antofagasta, and

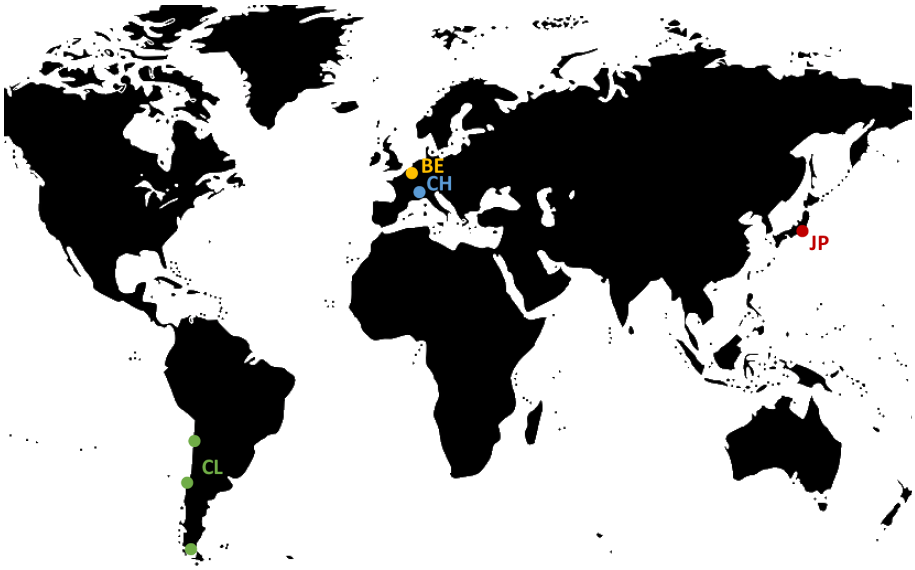


Figure 4.1: Localization on the world map of the four socio-environmental contexts that are studied in this research

around 1700 kWh/m^2 in Concepción. No data was available for Punta Arenas, but the value is expected to be much lower. Tokyo comes second with an annual sum of GHI of around 1400 kWh/m^2, in front of Lausanne having around 1300 kWh/m^2. Louvain-la-Neuve is the location with the lowest amount of GHI, i.e., around 1050 kWh/m^2.

Regarding indoor lighting levels, no cross-cultural study comparing lighting levels in office buildings was found. Therefore, recommendations in terms of illuminance were compared between the four socio-environmental contexts. The brightest indoor environments are supposed to be found in the Japanese context, with a recommended horizontal illuminance on the desk in offices of 750 lux according to the JIS Z 9110:2010 Standard. Then comes the European contexts, with a recommended illuminance on the desk in offices of 500 lux according to the EN 12464-1:2011 Standard, directly followed by the Chilean context, with a recommended illuminance on the desk in offices of 400 lux according to the NCH Elec. 4:2003 Standard.

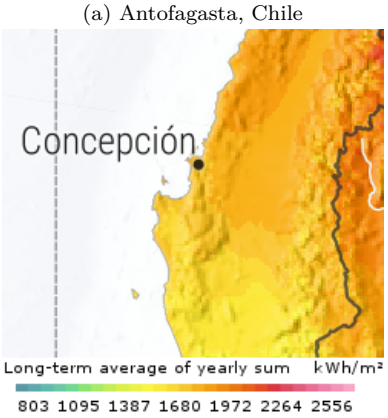
Based on these values, the lighting levels experienced indoor and outdoor should be slightly different between the Chilean, Japanese, and European contexts. Chile would offer the brightest outdoor environment, whereas Japan would offer the brightest indoor environments. Belgium and Switzerland would be relatively similar in terms of lighting levels.



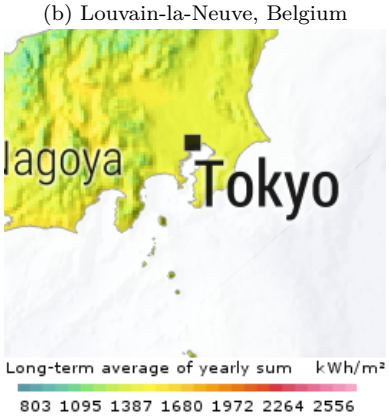
(a) Antofagasta, Chile



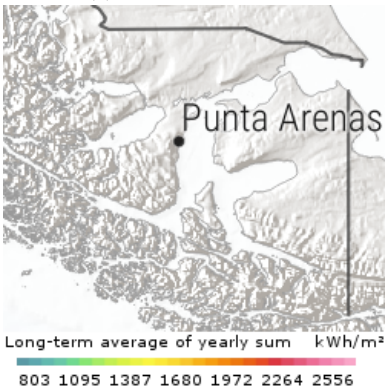
(b) Louvain-la-Neuve, Belgium



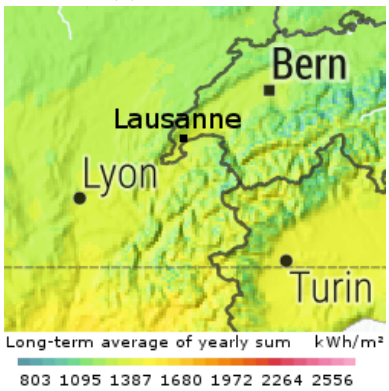
(c) Concepción, Chile



(d) Tokyo, Japan



(e) Punta Arenas, Chile



(f) Lausanne, Switzerland

Figure 4.2: Yearly sum of GHI [kWh/m^2] based on a long-term average for each studied city in each socio-environmental context (there was no data available for Punta Arenas)

4.1.3 Number of Subjects

For each of the four socio-environmental contexts, a certain number of discomfort glare evaluations had to be collected so that the hypotheses could be tested through statistical analyses. As explained in Section 3.2, the main research question that this study aims to answer is whether the socio-environmental context of a subject influences her/his discomfort glare perception from daylight in office buildings.

One of the principal statistical methods selected to answer this research question was the multiple logistic regression (Subsection 4.5.5). This nonparametric test allows to determine whether an independent variable, namely the socio-environmental context, has an influence on the dependent variable, namely discomfort glare perception. If this is the case, the multiple logistic regression also gives an estimate of to what extent this independent variable influences the dependent one.

The appropriate sample size required to test the main hypothesis had to be estimated considering the statistical method, but also considering the size of the effect that is being studied, and the statistical power desired for the study.

One way to define the minimum sample size for logistic regression analyses requires that the hypothesis has already been tested in a preliminary pilot study, or in other studies from the literature, and that results and odds ratio are already available [Hosmer et al. 2013]. Since no study had looked at the influence of the socio-environmental context on discomfort glare perception from daylight before, other ways had to be considered.

In a first step, the minimum required sample size was estimated through the software G*Power 3.1 [Faul et al. 2009] for a simple binary logistic regression. For this method, it was therefore considered that the data analysis would consist in looking at the behavior of a binary dependent variable, i.e., the subjective assessment of the visual scene, with $Y = 1$ standing for perceived discomfort due to glare and $Y = 0$ for no perceived discomfort, according to a binary independent variable, such as being Japanese ($X = 1$) against

being Belgian ($X = 0$). A minimum sample size of 195 discomfort glare evaluations (Figure 4.3) was computed by the software based on the following assumptions:

- The main statistical analysis consists of a logistic regression.
- A two-tailed test is required since the difference in discomfort glare perception between the Belgian and Japanese subjects could be observed in both directions. The Wald test on the parameter of the independent variable (Subsection 4.5.5) should therefore be executed considering both directions.
- Based on a similar existing field study [Konis 2014], it is hypothesized that the probability of perceiving discomfort due to glare in an office building when the subject is North American, which is considered as a similar socio-environmental context (as described in this research) to the Belgian one, is 65%.
- Since the literature suggests that Japanese subjects are more tolerant towards discomfort glare than Belgian subjects, it is also hypothesized that the probability of perceived discomfort due to glare in real offices for Japanese subjects is around 45%, namely 20% less than for the Belgian subjects.
- A Type I error rate of 0.05 and a power of 0.8 are determined, as suggested by [Green 1991; Uttley 2019] for a wide range of behavioral research areas.
- The R^2, namely the expected squared multiple correlation coefficient, is set to 0 since it is expected that there is no correlation between the tested binary independent variable, i.e., the socio-environmental context, and the covariates, i.e., the discomfort glare metrics.
- As previously mentioned, the dependent variable is a binary variable, and is expected to have identical distributions of Belgian and Japanese subjects.

Consequently, the minimum sample size to compare four socio-environmental contexts, and not two as implemented in the software, was determined by doubling the minimal sample size calculated by the software. A final minimum sample size of 390 discomfort glare

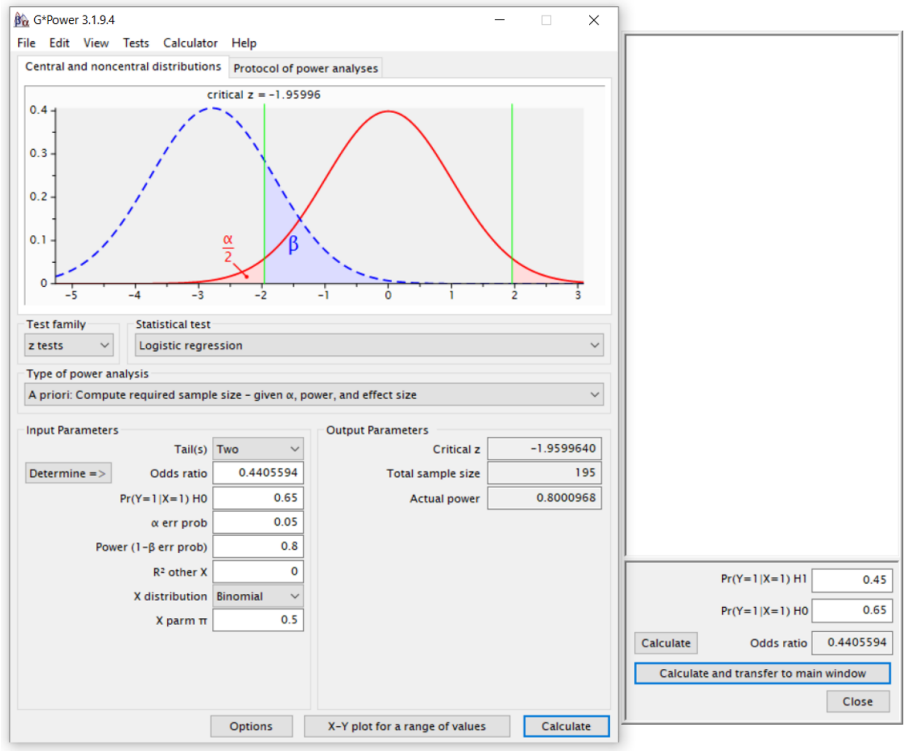


Figure 4.3: G*Power 3.1 software computing the minimum sample size to compare two socio-environmental contexts through logistic regression

evaluations was eventually determined. However, this sample size is based on the arbitrary assumption regarding the probability of perceived discomfort due to glare in real offices for the Japanese subjects, since no field study on discomfort glare conducted in a similar context could be found at that time.

More recently, a field study conducted in Indonesia showed that discomfort due to glare in real offices was reported for only 21% of the subjects. By implementing a probability of 21% instead of the estimated 45%, the software would have evaluated a minimum sample size for two socio-environmental contexts of 41 discomfort glare evaluations, hence a final minimum sample size of 82 discomfort glare evaluations for four socio-environmental contexts. It was therefore concluded a posteriori that the estimation made was

conservative and should ensure statistically valid analyses.

Additional methods to determine the minimum sample size for this study were also used to complement the results from the software G*Power.

One of these methods is based on a common rule-of-thumb stating that around 30 observations per group are required, although the rule is often criticized [Kar et al. 2013]. This rule considers that all the groups from the predictive variable are exposed to the same stimulus, and that 30 observations per group are sufficient to compare the response variable.

Since the discomfort glare stimulus was not controlled in this study, the sample size had to be defined accordingly, and the rule had to be adjusted. To compare the socio-environmental contexts in this study, it was assumed that the response variable, namely the assessment of discomfort glare made by the subjects, needed to be compared between each socio-environmental group for the situations with no discomfort due to glare (as measured by the metrics), but also for the situations with discomfort due to glare (as measured by the metrics). 30 observations per group were thus required for each one of the two situations. In total, considering 2 discomfort glare situations, 4 groups, and 30 observations per group, the sample size was computed as 240.

A second general method to determine the sample size was proposed by [Green 1991] for multiple correlation coefficients in a regression analysis considering the effect size of the study. The two-step method computes the required sample size as in Equation 4.1, and is based on a level of significance of 0.05, and a statistical power of 0.8.

$$\begin{gathered} f = \frac{R^2}{1 - R^2} \\ L = 6.4 + 1.65 \cdot m - 0.05 \cdot m^2 \\ N \geqslant \frac{L}{f} \end{gathered} \tag{4.1}$$

where:

R^2 is an index of effect size as defined by [Cohen 1988]

m is the number of predictors in the regression

N is the sample size

The sample size required for this study was evaluated through this method considering two predictors in the regression, namely the glare metric value and the socio-environmental context, and a small effect size ($R^2 = 0.02$). It was indeed expected that if the socio-environmental context had an influence on discomfort glare perception, its effect would be rather small. Based on these assumptions, a minimum sample size of 475 was computed.

The three different methods produced three minimum sample sizes, namely 390, 240, and 475. The lowest required sample size to compare discomfort glare evaluations made in four socio-environmental contexts was defined as the minimum of the three numbers, namely 240. At least 60 discomfort glare evaluations from 60 different subjects would have to be collected for each socio-environmental context since the groups have to be equal in size. However, this sample size of 240 was defined as the lowest required sample size, and a larger sample would be targeted, depending on what would be achievable from a practical and budgetary perspective.

4.1.4 Visual Scenes

To evaluate the difference in discomfort glare perception between different subjects, the visual scenes that are assessed by these subjects need to be comparable. This is the principle of measurement equivalence required for data comparison [Miller 2017]. Selection criteria were established in order to determine the conditions of equivalence under which the study could take place. By limiting the variations in the evaluated visual scenes through selection criteria, a fair basis of comparison was provided for the four socio-environmental contexts, and noise in the data was reduced.

The first selection criterion established that **the type of indoor environment had to be an office building, since this study**

was targeted at office environments. Furthermore, office buildings supporting a larger use of daylight than electric light, and where the electric lighting could be turned off would be favored.

Unfortunately, it was not possible to gain access to the same type of office buildings in each studied location. In Chile, the study took place in 4 multi-story governmental office buildings: one in Concepción, two in Punta Arenas, and one in Antofagasta. In Belgium, the study took place in seven multi-story university office buildings that were all located in the city center of Louvain-la-Neuve. In Japan, the study took place in seven multi-story university office buildings and six multi-story private office buildings. The 13 buildings were located within a radius of 60 km around Tokyo. In Switzerland, the study took place in four multi-story university office buildings that were all located on the campus, 5 km away from the city center of Lausanne.

Both open-plan and closed office spaces were eligible for the study. However, Section 2.1 showed that discomfort glare metrics usually do not perform similarly for both types of discomfort glare (i.e., saturation and contrast glare). In order to warrant similar performances of the metrics for each discomfort glare evaluation, the visual scenes had to be selected in such a way that the lighting conditions would produce the same type of discomfort glare for each evaluation. Since daylight is more often associated with saturation glare, the visual scenes were selected in order to reduce the potential for contrast glare from daylight, and to increase that for saturation glare. The subject's desk therefore had to be located as close as possible to a large daylight source.

The second selection criterion required that **only office workers having their desks located within approximately five meters from a window could participate in the study, no matter whether the office was an open plan or a closed one**.

Moreover, since office buildings are generally designed in order to reduce visual discomfort, it was expected that comfortable visual scenes would be more likely to occur than uncomfortable ones. For the statistical analyses, however, an even number of evaluations

were required in both categories (i.e., comfortable and uncomfortable visual scenes).

The third selection criterion was established to ensure that **the lighting conditions in the visual scenes maximized the potential for visual discomfort, and specifically for daylight discomfort glare occurrence**. In practical terms, this meant that the offices located next to a North-facing (South-facing in Chile) window would not be studied, that the study would only be conducted under sunny conditions, and possibly at times of the day when the potential for discomfort glare occurrence is high.

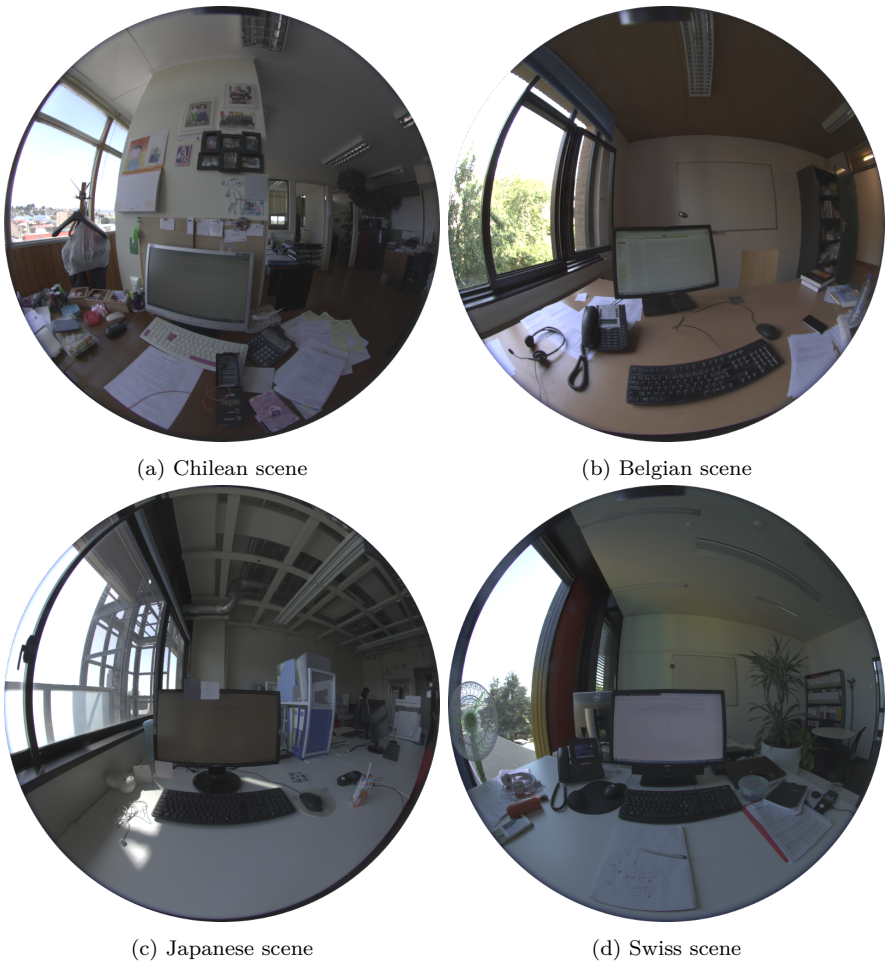
In addition, and as described in Subsection 4.1.1, the measurement of the visual scene through HDR photography after its subjective assessment required that the lighting conditions remained relatively stable throughout the session. On the one hand, the HDR photography technique took at least 30 seconds for each measurement, during which the conditions had to remain stable. On the other hand, the visual scene assessed by the subject had to be the same as the one measured afterwards through HDR photography, also requiring stable lighting conditions.

Therefore, the last selection criterion determined that **the study would only take place under clear sky conditions, in order to prevent clouds passing by and making the light levels vary inside the room**.

The study took place around summer time in each socio-environmental context, during the month(s) having a high probability of clear sky days:

- around March in Chile, and more specifically from the 6th to the 24th of March 2017
- around July and August in Belgium, and more specifically from the 15th of June 2017 to the 31st of August 2017
- around May in Japan, and more specifically from the 7th to the 25th of May 2018
- around July in Switzerland, and more specifically from the 2nd to the 31st of July 2018

In conclusion, the visual scenes evaluated in this study were randomly selected among the office desks meeting the selection criteria from the list of office buildings in which the study could take place. The office buildings were selected in advance for each socio-environmental context, in such a way that these buildings contained at least twice the minimum sample size of potential subjects for the context. Examples of visual scenes meeting the selection criteria are shown in Figure 4.4.



(a) Chilean scene (b) Belgian scene

(c) Japanese scene (d) Swiss scene

Figure 4.4: Examples of visual scenes from office desks located next to a window under clear sky conditions in each of the four socio-environmental contexts

4.1.5 Subjective Glare Assessment

This section describes how the measures of the subject's response to the visual environment were collected. To compare discomfort glare perception between different subjects, these subjects have to express how they perceive a visual scene, and more specifically how much discomfort due to glare they perceive in that visual scene. Two main methods have been found in the literature to collect a subjective assessment of discomfort glare.

The first method, which is the most common one, is the glare rating scale. After or while looking at a visual scene, subjects are asked to rate the amount of discomfort glare or of discomfort due to glare that they experience from the scene on a scale. In the literature, many different glare rating scales have already been used, although most of them are derived from two well-known ones:

- the 4-point Hopkinson's glare rating scale [Petherbridge et al. 1950]
  1. Just perceptible
  2. Just acceptable
  3. Just uncomfortable
  4. Just intolerable
- the 9-point (but 5 descriptor) De Boer's glare rating scale [De Boer 1967]
  1. Unbearable
  2.
  3. Disturbing
  4.
  5. Just admissible
  6.
  7. Satisfactory
  8.
  9. Unnoticeable

The glare rating scales are usually uni-polarized, going from none or non-perceived glare to intolerable glare, but the number of response

points can vary considerably. For example, 4 response points were used for a glare rating scale in [Fisekis et al. 2003], 5 response points in [Tuaycharoen et al. 2007], 6 response points in [Kim et al. 2012b], 8 response points in [Shin et al. 2012], 9 response points in [Van Den Wymelenberg 2012b], etc.

More recently, a 4-point glare rating scale introduced by [Osterhaus et al. 1992] seems to have been adopted by a tacit agreement, as it has been used frequently in recent discomfort glare studies [Kuhn et al. 2013; Wienold et al. 2006; Konstantzos et al. 2016; Yamin Garretón et al. 2014; Painter et al. 2009; Sarey Khanie et al. 2017].

Although the scale was first used with descriptions of the meaning of the response points using temporal indicators, the labels of the four response points are now being used on their own, as follows:

- ○ Imperceptible
- ○ Noticeable
- ○ Disturbing
- ○ Intolerable

The second method to collect a subjective assessment of a visual scene regarding discomfort glare is through a drawing-based question. After or while looking at a visual scene, subjects are asked to mark any discomforting bright areas on a drawing representing the visual scene. The intensity of perceived discomfort due to glare cannot be collected from this method, but it informs whether discomfort glare is being experienced, and its source. The drawing-based method has been used as a subjective assessment method in [Hirning et al. 2014; Fisekis et al. 2003; Cauwerts 2013] for instance.

The drawing-based method is best suited for studies in which the same visual scene is being assessed by different subjects. A detailed drawing of the visual scene including visual elements such as windows or lamps can then be produced, and subjects can mark the discomforting areas on the drawing of the visual scene easily by referring to these visual elements.

In the case of this field study, however, each subject had to assess a

unique visual scene, i.e., the one from her/his own office desk. Since it was not possible to know in advance which office desk would be evaluated, especially because the subjects were recruited on the day of the study (Subsection 4.1.10), a drawing of a universal office desk view would have been required. This universal drawing would have implied that, except for a desk and a computer, no other visual elements could have been included in the drawing. On the one hand, the subject could have had difficulties marking discomforting areas on the drawing without important visual elements to refer to. On the other hand, an accurate interpretation of the discomforting areas as intended by the subject could also have been confusing for the investigator. Furthermore, the method did not allow the investigator to collect the intensity of discomfort due to glare generated by the marked area(s).

For these reasons, it was decided to fall back on glare rating scales for the subjective assessment. However, these scales also endure several disadvantages, as highlighted in [Fotios 2015], and should be used carefully.

The first disadvantage of using a glare rating scale is that the subject's attention is focused on the potential glare. Subjects are invited to complain about their environment through the rating scales, whereas, in some cases, they would not have recognized spontaneously that this environment was causing discomfort in the first place. To take into account this potential bias, it was decided to include a prior question. This question would allow the subjects to report discomfort due to glare spontaneously, without drawing attention on this specific aspect of the visual scene. This prior subjective assessment was implemented through an Open-Ended Question (OEQ), namely a question to which the subject is free to answer whatever he/she wants, and in which discomfort glare was not mentioned.

As a result, the first method to collect a subjective assessment of the visual scene in the questionnaire consisted of a question about the satisfaction with the lighting conditions, followed by a conditional OEQ.

At the moment, are you satisfied with the lighting conditions in your office?

- ○ Unsatisfied
- ○ Rather unsatisfied
- ○ Rather satisfied
- ○ Satisfied

If the subject did not answer that he/she was Satisfied, then he/she was asked the reason why through the OEQ.

Which element(s) bother(s) you in the current lighting conditions?

This subjective assessment method had to be used as the first one in the subjective assessment part of the questionnaire, in order for the subject not to be reminded that the focus of the study was discomfort glare.

The second disadvantage of glare rating scales is the lack of an explicit "no glare" option. The lowest category of many discomfort glare scales tends to insinuate that there is discomfort glare in the visual scene although it is not perceived by the subject.

This can be observed in the three scales displayed before, as the labels of the lowest category are Just perceptible, Unnoticeable, and Imperceptible.

Moreover, in most glare rating scales, the boundary between the categories standing for "no glare" and those standing for "glare" is not clear and the labels are subject to interpretation.

Although it made the results of this study more difficult to compare to those of previous studies, a glare rating scale slightly different from those that have been commonly used in the literature was chosen in order to avoid the previous bias.

At the moment, do you feel discomfort due to glare?

- ○ No, no discomfort
- ○ Yes, a small discomfort

○ Yes, a moderate discomfort

○ Yes, a large discomfort

This scale was introduced in a field study on discomfort glare perception a few years before [Konis 2014]. Its first characteristic is the presence of the "No/Yes" binary classifier allowing to clearly discriminate between "no glare" and "glare" situations.

A second characteristic is the use of a common descriptive term in the four response points, namely "discomfort". By linking this term with a graduated system, namely "no < small < moderate < large", the response points can be easily understood by the subject, and without requiring too much interpretation.

Because of these characteristics, this glare rating scale, here referenced as the glare rating scale A, was used as the second subjective assessment method, and the question was asked directly after the OEQ in the questionnaire.

Moreover, since the study took place in real office buildings, there was no way of controlling that the discomfort glare perceived by the subject, if any, was directly related to daylight.

It could have happened that the electric lighting was producing discomfort glare, although buildings where electric lighting could be turned off were preferred. It could also have happened that the computer screen on which the subject was answering the questionnaire caused veiling glare.

The detection of these situations was needed in order to remove the evaluations from the dataset, since the focus of this study was on discomfort glare from daylight, and the daylight discomfort glare metrics are not effective to detect other types of glare than discomfort glare from daylight.

To detect whether the perceived discomfort was linked to daylight, a multiple-choice question was asked to the subjects who had previously selected Yes, a small discomfort, Yes, a moderate discomfort, or Yes, a large discomfort in the glare rating scale.

What is the source of your discomfort?
(Multiple replies possible)

- ☐ The window
- ☐ The wall
- ☐ The computer screen
- ☐ The artificial lighting
- ☐ Other: _____

A last limitation of glare rating scales, and of rating scales in general, is the choice of a specific number of response points. Some scales use an even number of categories, whereas others use an odd number, implying that the presence of a middle response point is not fixed. The issue of using or not a middle response point is still open for debate [Garland 1991; Weijters et al. 2010], and could have implications on subjects' interpretation of a scale.

Consequently, a 5-point glare rating scale was used as a second rating scale, here referenced as the glare rating scale B, and as the third subjective assessment method in the study, to check for bias related to the number of response categories. The 5-point scale is similar to the one used in [Tuaycharoen et al. 2007], and is an adaptation of the continuous scale having these labels used in different studies with Japanese subjects [Iwata et al. 1992b; Mochizuki et al. 1997; Mochizuki et al. 2005]. It was chosen in order for the labels to be easily translated into Japanese, and it was modified in such as way that it can be used as a rating scale and not as a continuous scale.

At the moment, how would you rate glare in your field of view?

- ○ Intolerable
- ○ Uncomfortable
- ○ Acceptable
- ○ Perceptible
- ○ Imperceptible

Moreover, the labels of the scale B were printed in a reverse order of magnitude than the glare rating scale A. This was done on purpose, to check that subjects were correctly reading the question through the consistency of their answers between the glare scales A and B.

After having conducted the study in the first two socio-environmental contexts, i.e., in Chile in March 2017 and in Belgium around July 2017, the subjective assessments of the visual scenes were analyzed. Following the results described in Section 8.2, the 4-point glare scale suggested in [Osterhaus et al. 1992] was added as a fourth subjective assessment method for the two remaining socio-environmental contexts (i.e., Japan in May 2018 and Switzerland around July 2018).

At the moment, how would you rate glare in your field of view?

- ○ Imperceptible
- ○ Noticeable
- ○ Disturbing
- ○ Intolerable

This 4-point glare rating scale, here referenced as the glare rating scale C, was added at the end of the subjective assessment part of the questionnaire, so as not to influence the answers to the previous subjective assessment methods. On the one hand, scale C would promote the comparison of part of the results with existing discomfort glare studies having used the same scale. On the other hand, it would help to understand results regarding the number of response categories, by comparing glare rating scale B and C, which have similar labels.

In total, the subjective assessment methods consisted in an OEQ and two different glare rating scales (A and B) for the Chilean and Belgian socio-environmental contexts, and an OEQ and three different glare rating scales (A, B, and C) for the Japanese and Swiss socio-environmental contexts.

These subjective assessment methods were not randomized in order to always have the OEQ before the glare rating scales (to avoid

drawing the subject's attention to glare before the OEQ) and scale A before the two other scales (to avoid biasing the subjective assessments made on this first scale as it would be the one used for the analyses). Moreover, for each subjective assessment method mentioning discomfort glare, a short description of glare was given.

Glare is an excess of light inducing annoyance or discomfort.

Using different subjective assessment methods was a conscious choice that would enable the study of one of the experimental biases, i.e., the glare rating scales, which is the focus of the second additional research question. The 4-point glare rating scale A was, however, chosen as the one upon which the statistical analyses to study the influence of the socio-environmental context would be based. The reasons for this choice were that a binary variable, i.e. "0 (No, no glare)/1 (Yes, glare)", as well as the intensity of glare, i.e. "small < moderate < large" could both be outputted from this scale, and that it was expected to generate less bias than the two others. The subjective assessments made through the OEQ will also be considered in these statistical analyses.

4.1.6 Questionnaire

This section describes the questionnaire used for the measures of the subject's profile, as well as for the subjective glare assessments and measures of some contextual variables. The subject's profile consists in the demographic, physiological, and psychological factors needed to answer the first additional research question.

The questionnaire was designed so that it could lead the subject through all the steps of the study session. Moreover, since no compensation was given to the subject for their time, and because a large sample had to be collected, each session needed to be as quick as possible to complete, hence the questionnaire had to be short.

Three main elements were needed in the questionnaire, namely the gathering of general information, a visual task, and the subjective assessment of the visual scene (Subsection 4.1.5).

The gathering of general information was the longest part of the

questionnaire.

First, the acclimatization of the subject to the socio-environmental context was verified through a multiple-choice question.

For how long have you lived in Chile/Belgium/Japan/Switzerland?

- ○ For less than 6 months
- ○ For less than 1 year
- ○ For less than 2 years
- ○ For less than 5 years
- ○ For more than 5 years
- ○ Forever

According to the literature (Subsection 2.2.3), the information required to determine a subject's acclimatization to a socio-environmental context is to know whether the subject has been living for the last two years in that context. In the questionnaire, more detailed information regarding the time spent in the country was required from the subject, as well as her/his country of origin, and a list of other countries where he/she had lived for more than six months. This information was collected so that a more detailed profile of the subject's acclimatization state could be established, if needed, to better understand the results.

Then, the information regarding the list of additional factors which were targeted by the first additional research question was collected. Two factors, the indoor air temperature and the time of the day, were not recorded through the questionnaire, but through measurements (Subsection 4.1.7), since they were not related to the subject. Moreover, as previously mentioned, no specific information was required for the investigation of some experimental biases, which is the focus of the second additional research question, but the protocol of the study has been established with this research question in mind (several subjective assessment methods used).

Some of the 11 remaining factors usually require the use of a specific questionnaire to be evaluated correctly. This is the case for the

chronotype, which is best evaluated through the Munich Chronotype Questionnaire (MCTQ) [Roenneberg et al. 2003], or the emotional state of the subject through the Positive And Negative Affect Schedule (PANAS) [Watson et al. 1988] for instance. These specific questionnaires are, however, time-consuming and could not be implemented in this study. Therefore, only the judgments provided by the subject in response to the following questions were used for the determination of the factors. The questions are derived based on previous studies' questionnaires [Wienold 2009a; Van Den Wymelenberg 2012b; Kent 2016] and on the comments received during the pilot study.

1. Gender of the subject

   What is your gender?

   ○ Female
   ○ Male

2. Age of the subject

   What is your month and year of birth?

   Month: _____
   Year: _____

3. Chronotype of the subject

   Do you consider yourself to be more active and alert in the morning or in the afternoon?

   ○ Definitely in the morning
   ○ Rather in the morning
   ○ Rather in the afternoon
   ○ Definitely in the afternoon
   ○ I don't know

4. Glare sensitivity of the subject through self-assessment

   Do you consider yourself sensitive to glare?

   0 (Not sensitive) 10 (Very sensitive)

5. Visual acuity of the subject through her/his optical correction

Do you use glasses or contact lenses to work?

- ○ Glasses
- ○ Contact lenses
- ○ None

6. Iris pigmentation of the subject

What is the color of your eyes?

- ○ Dark brown
- ○ Light brown
- ○ Blue
- ○ Green
- ○ Grey
- ○ Other: _____

7. Physical state of the subject

How do you feel physically right now?

- ○ 
- ○ 
- ○ 
- ○ 
- ○ 

8. Emotional state of the subject

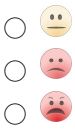
How would you rate your current mood?

- ○ 
- ○ 
- ○ 
- ○ 
- ○ 

9. Fatigue of the subject

How would you rate your current fatigue?

- ○ 
- ○ 



10. Caffeine ingestion of the subject

    Have you had coffee, tea, or an energy drink since you got up? (Multiple replies possible)

    - ○ No
    - ○ Yes, coffee
    - ○ Yes, tea
    - ○ Yes, energy drink
    - ○ Other: _____

11. Attractiveness of the view through the window

    How do you like the view through the window at the moment?

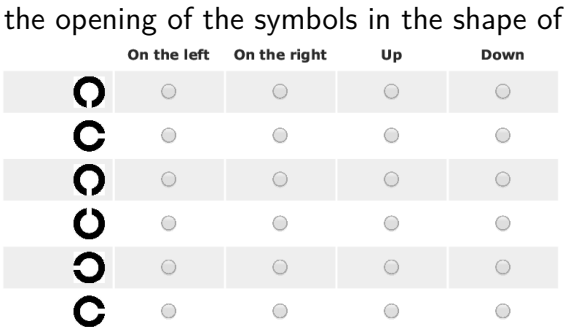
To ensure that the results could be deepened if necessary, a few more pieces of information were collected:

- if the subject needed an optical correction, the reason for the optical correction
- the handedness (right-handed, left-handed, or ambidextrous) of the subject
- if the subject had ingested caffeine, the time since the ingestion
- the satisfaction with the thermal conditions
- if the subject was not fully satisfied with the thermal conditions, the reason for her/his dissatisfaction (thermal sensation)

Besides the gathering of general information, the second principal element of the questionnaire was the visual task. The main reason for a visual task was to ensure that the subject was working on the computer screen for some time before making the subjective assessment of the visual scene.

Since, in the beginning, it was supposed that the performance of the subjects in performing the visual task could be compared and used to determine their visual acuity, a visual task based on Landolt rings was chosen [Bach 1996].

More specifically, the visual task consisted in three series (one easy, one moderate, and one difficult) of six Landolt rings oriented in four different ways, namely left, right, up, and down. The subject had to locate the orientation of the opening of each ring. The difficulty was increased between each series by decreasing the size of the rings. However, each subject was using her/his own computer to answer the questionnaire, making the resolution and contrast of the displayed Landolt rings vary. The visual task could thus not be used to assess or compare the subjects' visual acuity.



The visual task was located before the subjective assessment part in the questionnaire, to ensure that the subject visual field was focused on the computer screen. Furthermore, the visual task answers were used to detect acquiescence response bias and cleanse the dataset, as explained in Subsection 4.3.3.

Finally, the subjective assessment of the visual scene consisted principally in an OEQ and two or three different glare rating scales, according to the socio-environmental context. The questions of this part of the questionnaire are detailed in Subsection 4.1.5. The questions of the subjective assessment part of the questionnaire are repeated twice, once for each discomfort glare evaluation made by the subject.

The questionnaire was implemented with the open-source survey software platform LimeSurvey version 2.00+, and hosted on the university server. A first version of the questionnaire was tested during the pilot study, as explained in Subsection 4.1.9. It was modified according to the results, to include two discomfort glare evaluations. Therefore, the visual task followed by the subjective assessment were repeated twice, and the gathering of information was made in between. The final questionnaire took around six to seven minutes to complete on its own.

Moreover, the questionnaire had to be established in the spoken language of each socio-environmental context in which the study took place. The questions were first written in English, based on published questionnaires of discomfort glare studies [Hirning 2014; Wienold 2009a], and translated into French by the investigator who was fluent in both languages.

The questionnaire also needed to be translated into Spanish, for the Chilean context, and to Japanese, for the Japanese context. To do so, three people who were native-Spanish or Japanese speakers, and who were also fluent in French or English, helped for each translation. The questionnaire was first translated from one of the two original languages (French or English) to the target language (Spanish or Japanese) by the first person. When this was done, the original and the translated questionnaires were sent to a second person for her/him to correct the translation made by the first person. A third person received only the corrected translation of the questionnaire and was asked to translate it back to one of the two original languages. This last version was then checked by the investigator, and corrections were made with the help of the third person, if the meaning of a translated question was not exactly as the one intended in the original questionnaire.

The four final versions of the questionnaire are available in appendices B, C, D, and E. The Spanish version was used for Chile, the French version was used for Belgium and Switzerland, the Japanese version was used for Japan, and the English version was used for Switzerland. Switzerland was the only socio-environmental context

for which the questionnaire could be completed in two languages, as the university buildings where the study took place have a very international public accustomed with the English language.

4.1.7 Measurements

This section describes how the measures of the environment were collected. Besides the data collected through the questionnaire, measured data was required to determine:

1. the discomfort glare metric values
2. the stability of the lighting conditions
3. some of the factors to be investigated for the first additional research question

As mentioned in Subsection 4.1.1, when studying discomfort glare, an important step lies in the calculation of the discomfort glare metric values that represent the discomfort glare stimulus in the visual scene. In a field study, it is expected that the visual scenes evaluated by the subjects are all different, resulting in different discomfort glare stimuli. To analyze and compare the subjective assessments made by the subjects, the discomfort glare stimuli have to be measured. Up to now, the best way of defining a discomfort glare stimulus has been through the discomfort glare metric values.

The discomfort glare metric values corresponding to a visual scene can be calculated from a luminance map of the scene. Luminance maps are images in which each pixel represents the luminance of the corresponding portion of the captured FOV [Hirning et al. 2010]. Nowadays, these luminance maps have become essential to evaluate discomfort glare in real visual scenes, as they enable the researchers to collect high-resolution luminance data within a large FOV quickly and efficiently [Hirning et al. 2010]. To generate these luminance maps, HDR photography was used.

HDR Photography

This subsection includes amended parts of a tutorial article accepted for publication in LEUKOS [Pierson et al. 2019a], of which

the accepted manuscript is reproduced in Appendix J with permission of the Illuminating Engineering Society.

HDR photography consists in capturing multiple exposures of a scene from an identical point of view and merging them in order to obtain an image with a higher range of brightness, namely an HDR image [Pierson et al. 2019a]. After calibration, a luminance map is produced from the HDR image. This luminance map can be used to derive the discomfort glare metric values of the visual scene through the Evalglare program [Wienold et al. 2004], as explained in Subsection 4.2.6.

To generate a luminance map via HDR photography, a sequence of Low Dynamic Range (LDR) images is thus required, as well as spot luminance and vertical illuminance measurements for the calibration.

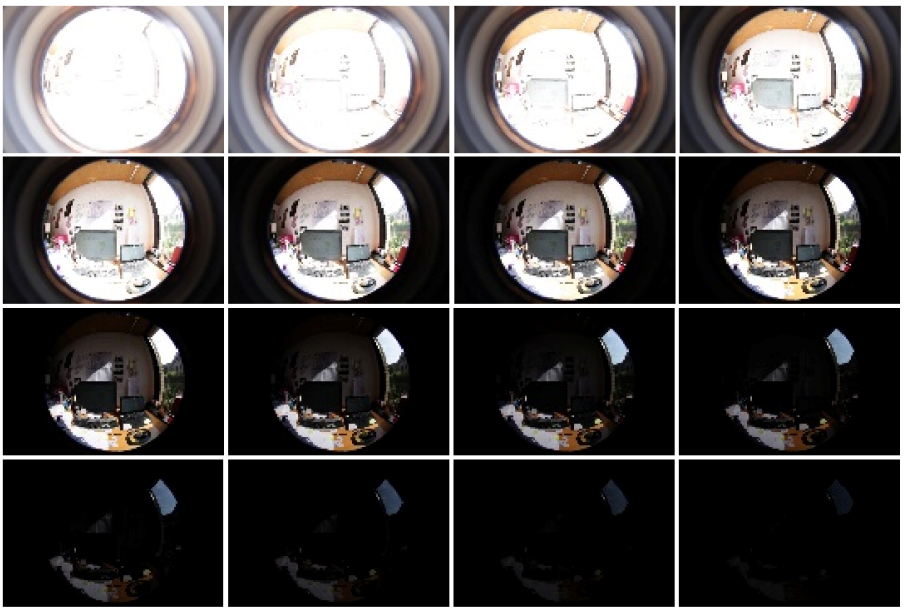


Figure 4.5: Sequence of 16 multiple exposure LDR images, showing a fisheye view of the subject's FOV, required to generate an HDR image

For each discomfort glare evaluation, a sequence of 15 LDR fisheye images having different exposures was captured from the subject's

point of view (Figure 4.5) in order to create a 180° HDR image. The sequence was captured through a Digital Single-Lens Reflex (DSLR) camera fitted with a fisheye lens, and the equipment was mounted on a tripod and controlled remotely by a computer. Detailed information about the set-up of the equipment is given in Subsection 4.1.8. The camera settings were set according to Table 4.2. The sequence, of which the capture was automated via a bracketing software, extended from an overexposed image to an underexposed image, with 1 EV stop between each image produced by varying the exposure time (Figure 4.5). Moreover, when the sun was in the FOV, an Neutral Density (ND) filter was used (Subsection 4.2.5).

Settings	
Film speed	ISO 100
White balance	Daylight (5200K)
Exposure mode	Manual
Focus mode	Manual
Focus value	Infinite
Image quality	Largest
Image type	JPEG
Picture style	Neutral
Peripheral correction	Disabled
Color space	sRGB
Lens aperture	Mid-range (f/8 or f/11)

Table 4.2: Camera settings used for the capture of multiple exposures in order to generate the HDR images

Furthermore, two spot luminance measurements were made with a spot luminance meter on two targets (one gray and one white) in the visual scenes during the LDR sequence, and two vertical illuminance measurements were made with a luxmeter next to the lens of the camera before and after the LDR sequence. These measurements are necessary to scale respectively the relative luminance values embodied in the HDR image to the absolute luminance values of the scene, and to check the validity of the generated 180° luminance map.

The detailed procedure that was used to generate the 180° lumi-

nance maps is similar to the one described in the tutorial article [Pierson et al. 2019a], although the steps were not applied in the same order. The software used for the generation of the luminance maps consisted of the Radiance suite of programs version 5.2 [Ward 1987], including version 2.08 of evalglare [Wienold et al. 2016] to process the images, and Photosphere version 1.8.21U [Ward 2009] to apply the photometric adjustment. As recommended in the tutorial article [Pierson et al. 2019a], the camera response function, the fisheye view coordinates, the distortion function, the vignetting curves, the ND correction function, and the luminous range of the camera were defined beforehand and applied to all images.

The calibration procedure was automated through an R script on Linux, and consisted of:

1. selecting the useful exposures
2. merging the exposures to generate an HDR image by using the predefined camera response function
3. nullifying the exposure value of the HDR image
4. correcting the vignetting of the HDR image by using the predefined vignetting curves
5. cropping the HDR image by using the predefined fisheye view coordinates
6. adjusting the projection of the HDR image by using the predefined distortion function
7. correcting the alterations of the HDR image due to the ND filter if one was used, by using the predefined ND correction function
8. editing the HDR image header by using the predefined projection type and real viewing angle
9. resizing the HDR image

The vignetting correction curves were devised by assuming that the lens had an equidistant projection. However, since the lens had an equisolid-angle projection, the applied vignetting correction curves contained an error. The vignetting correction step was detailed

correctly in the tutorial article [Pierson et al. 2019a] to prevent this issue in the future. But it was decided not to generate again the luminance maps with the corrected vignetting curves since the error in vertical illuminance was shown to be lower than 0.25%, and negligible in regard to the error related to the photometric adjustment.

As recommended in the tutorial article [Pierson et al. 2019a], the photometric adjustment of the HDR images with the measured spot luminance values was done manually in a second step, by applying a proper scaling factor to each image through the Photosphere software. The gray targets were first manually located in the displayed HDR image in Photosphere viewer. The calibration was then automatically applied to every pixel of the HDR image by inputting one of the measured spot luminance values to its corresponding target area in Photosphere.

In summary, the measured data required to determine the discomfort glare metric values were the luminance maps of the FOV generated on the basis of a sequence of LDR images, the two spot luminance measurements, and the two vertical illuminance measurements.

Secondly, as explained in Subsection 4.1.1, unstable lighting conditions could have made the visual scene evaluated by the subject change before the LDR sequence was captured. To prevent this issue, the stability of the lighting conditions was checked through the maximum deviation in horizontal illuminance, defined by Equation 4.2 in Subsection 4.2.2.

The maximum deviation in horizontal illuminance was calculated based on measurements of horizontal illuminance collected automatically every 20 seconds. An illuminance sensor was placed on the subject's desk and remotely controlled by a computer to record horizontal illuminance measurements during the entire session.

In summary, the measured data required to determine the stability of the lighting conditions were the automated measurements of desk horizontal illuminance.

Two additional factors that are required for the first additional research question of the study could not be evaluated through the questionnaire. These factors are the air temperature and the time of the day.

One-time measurements of relative humidity and air temperature were collected by the investigator via a humidity and temperature sensor during each session, while the subject was answering the questionnaire. In addition, the date and time at which the session started were also recorded manually by the investigator. This information was digitally encoded at the end of each study day.

In summary, the measured data required to determine some of the factors to be investigated for the first additional research question were the relative humidity, the air temperature, and the date and time of the session start.

4.1.8 Setup of Equipment

As the study took place directly in the subjects' office, the setup of the study varied according to the office layout. The measurement of the visual scene was collected from the usual location of the subject when sitting at her/his desk, and the questionnaire, including the subjective assessment of the visual scene, was completed by the subject sitting at her/his desk from her/his personal computer. Therefore, the subject and the measuring equipment controlled by the investigator had to take turns in front of the office desk so that the same FOV was being evaluated through respectively the subjective assessment and the measurement, as shown in Figure 4.6.

When no measurements were being taken, the investigator stood back from the desk so as not to be in the subject's FOV or create a shadow. After the subjective assessment of the visual scene was made, the subject was asked to stand back from her/his desk and stay behind the equipment and investigator while the measurement of the visual scene was being taken.

Regarding the equipment required for the study, it had to be compact in order to be easily set in place of the subject sitting position, as well as portable in order to be transported by only one person



(a) Subjective assessment (b) Measurement

Figure 4.6: Example of the setup of the study taking place in a real office

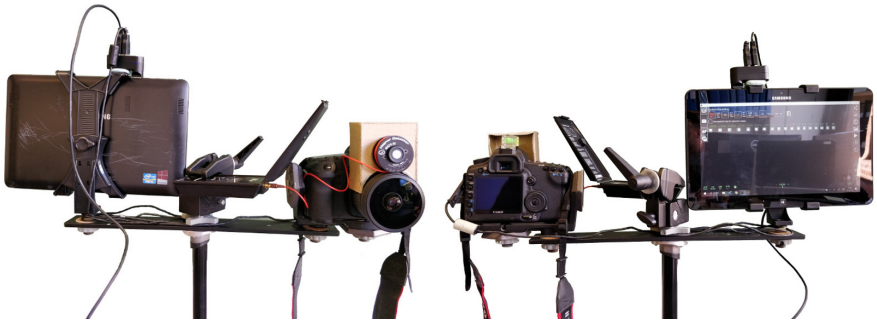
from one office to the other without dismantling. The setup of the equipment was thus designed in such a way that almost all instruments were mounted on one compact portable support.

As detailed in Subsection 4.1.7, the measurements collected during a discomfort glare evaluation consisted in:

- a sequence of LDR images
- two spot luminance measurements
- two vertical illuminance measurements
- automated measurements of desk horizontal illuminance
- relative humidity
- air temperature
- date and time of the start of the session

The sequence of 15 LDR fisheye images having different exposures was captured through a DSLR camera fitted with a compatible circular fisheye lens. A Canon EOS 5D Mark II camera and a Sigma EX DG 8mm f/3.5 fisheye lens were used for the study. The camera was remotely controlled by a tablet computer, and both the camera and the tablet were mounted on a tripod fitted with a double support plate (Figure 4.7).

The camera was connected to the tablet via a USB connection, and the software used to remotely control the camera was qDslrDash-



(a) Front view (b) Back view

Figure 4.7: Setup of the equipment mounted on the tripod: the tablet computer, the vertical luxmeter, and the camera fitted with a fisheye lens

board version 3.5.5 [Hubai 2014]. The tablet computer was also connected to WiFi, so that the investigator could send the link of the online questionnaire to each subject at the start of the session.

The tripod was placed (in place of the subject sitting position), with the lens of the camera at the same position and height as the subject's eyes. A spirit level was attached to the camera to ensure that it was perfectly horizontal when capturing the sequence of LDR images. Moreover, when the sun was in the FOV, a Kodak Wratten 3.0 ND filter was used to ensure that the entire range of luminance was captured (Subsection 4.2.5).

Two spot luminance measurements were required to adjust photometrically the HDR image with absolute luminance values of the scene. The spot luminance values were measured on two neutral color targets in the FOV, in areas with mid-range luminance values and not prone to lens flare or pixel overflow, during each sequence of LDR images. The spot luminance measurements were taken by the investigator with a Konica Minolta LS-110 luminance meter recently calibrated (7th of September 2016) and held as close as possible to the camera lens (Figure 4.6b).

Vertical illuminance measurements were also needed in order to check the validity of the luminance maps generated through HDR photography. The validity check consists in comparing the total

lighting energy embodied in the HDR image to the total lighting energy reaching the luxmeter placed just above the lens. Two vertical illuminance measurements were taken at the beginning and at the end of the capture of LDR images to analyze the stability of the lighting conditions during the measurement and to check the luminous balance of the generated luminance map. A Hagner digital luxmeter EC1-X recently calibrated (14th of September 2016) displayed the measured vertical illuminance values that were manually collected by the investigator (Figure 4.8b). The luxmeter was positioned vertically on top of the fisheye lens so that, if the two were not perfectly aligned, the lens was shading only the light reflected from the ground (Figure 4.8a).



(a) Sensor of the luxmeter aligned with the fisheye lens

(b) Vertical illuminance measurement displayed by the luxmeter

Figure 4.8: Setup of the luxmeter for the vertical illuminance measurements

The stability of the lighting conditions was also monitored through measurements of desk horizontal illuminance collected automatically every 20 seconds for three out of the four socio-environmental contexts. Unfortunately, the equipment was not available at the time of the Chilean study, and the stability of the lighting conditions was analyzed with the vertical illuminance measurements only. For the three other contexts, a Konica Minolta CL-200A luxmeter recently calibrated (purchased new on the 8th of June 2017) was placed on the subject's desk (Figure 4.9). The luxmeter was remotely controlled by the tablet computer via the Data Management Software CL-S10w version 1.40 [Konica Minolta 2011], so that a horizontal illuminance measurement was recorded every 20 seconds during the entire session.



Figure 4.9: Horizontal luxmeter and humidity/temperature pen placed on the subject's desk during each study session

Moreover, the relative humidity and air temperature were measured by an EXTECH 445580 humidity and temperature pen positioned on the subject's desk (Figure 4.9). The measurements were displayed on the pen and collected manually by the investigator while the subject was completing the part of the questionnaire in which general information was gathered. All the measurements and data collected manually by the investigator, i.e., the spot luminance measurements, the vertical illuminance measurements, the air temperature, the relative humidity, and the date and time of the session, were written in a table and stored digitally afterwards.

4.1.9 Pilot Study

The study protocol developed for the study of the socio-environmental context was tested via a pilot study. The pilot study was conducted to test the questionnaire and the procedure of the study. The measuring instruments had not yet been calibrated.

Qualitative data was expected from the pilot study, such as the feedback from the subjects on the questionnaire. Therefore, only a small sample of subjects was investigated. The pilot study was conducted in one university building in Louvain-la-Neuve (Belgium)

at the end of summer in 2016 under clear sky conditions. Prior to the study, 30 office desks located in rooms with access to daylight had been selected, and the office workers had given their consent to take part in the pilot study.

The timeline of the pilot study (Figure 4.10) started with the investigator entering the room. Without specifying that the study was about discomfort glare, explanations were given to the subject: the subject would have to answer a questionnaire, which would be sent by email, and physical measurements from her/his office desk would be taken afterwards. After the explanations, the investigator directly asked to open the shading devices (if they were closed), and to turn off the electric lighting (if on). The subject could then start answering the questionnaire with the part where general information was gathered, while adapting to the new lighting conditions. In the meantime, the date, time, air temperature and relative humidity were recorded by the investigator. After all the information listed in Subsection 4.1.6 was collected through the questionnaire, the subject performed the visual task and made the subjective assessment of the visual scene. At the end of the questionnaire, the investigator asked the subject to stand back from her/his office desk, so that the measuring equipment could be put in place. Both the investigator and the subject stood behind the equipment while a sequence of LDR images as well as spot luminance and vertical illuminance measurements were taken. At the end, the shading devices and the electric lighting were reset according to the subject's preferences, and the investigator left the room.

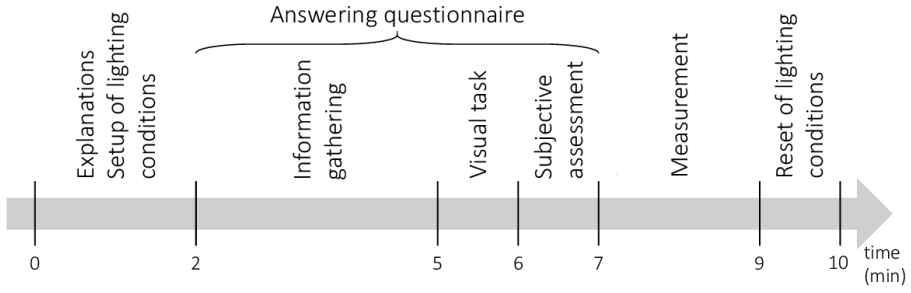


Figure 4.10: Timeline of the protocol of the pilot study for one subject

One session of the pilot study lasted on average ten minutes. In total, 27 subjects took part in the pilot study between the 17th and the 25th of August 2016. The collected data was processed as detailed in Section 4.2. Because the reliability of the measurements was uncertain since the instruments were not yet calibrated, limited statistical analyses were run on the data.

After removing two outliers, for which the sun was in the visual scene, the data showed that the lighting conditions were relatively dark at the office desks. The median measured vertical illuminance at eye level was around 300 lux (Figure 4.11). This is most probably explained by the fact that the selection criteria for the pilot study were not as strict as described in Subsection 4.1.4, and the office desks were selected at the only condition that there was a window in the room. This condition alone did not ensure that the desk was located next to the window, as is the case in Figure 4.12, resulting in low lighting levels.

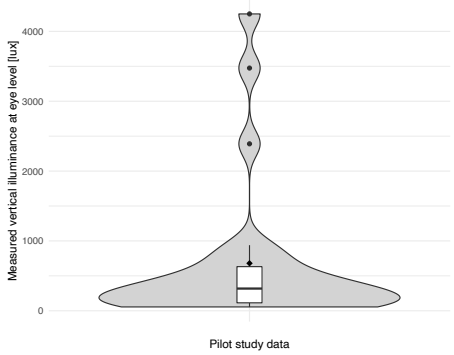


Figure 4.11: Violin plot, representing the density of the data, and box plot, representing the distribution of the data, for the vertical illuminance at eye level measured during the pilot study; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

In this respect, it is surprising that eight of the subjects (more than 30%) of the pilot study reported discomfort glare (Table 4.3), especially since five of them were experiencing a vertical illuminance level at the eyes lower than 500 lux.

One explanation might be that these subjects felt discomfort due



Figure 4.12: Visual scene of the pilot study, in which the office desk was located far from the window

Data points	No discomfort	Discomfort (small/moderate/large)
25	17	8
100%	68%	32%

Table 4.3: Summary of the subjective assessments made on the 4-point glare rating scale A during the pilot study

to too large a contrast in the FOV (contrast glare), instead of too bright light (saturation glare). However, for 4 out of the 5 subjects, contrast glare was not reported by the discomfort glare metrics representative of contrast glare (CGI and DGI values below 13).

A second explanation, supported by the observations of the investigator, is related to the subjects' expectations. Since the subjects were told at the beginning of the session that the study was looking at the comfort of working environments, they expected the investigator to measure the actual conditions in which they were working. As the lighting conditions were modified by the investigator before any measurements were taken, the subjects tended to complain, and this behavior was reflected in their subjective assessment of the visual scene. Therefore, even though the modified environment was not markedly discomforting, the subjects had a tendency to

complain.

To avoid collecting biased data because of this issue, it was decided to adapt the protocol.

A possibility of adaptation was to ask the subject directly to set the lighting conditions to a "just discomforting" situation. More specifically, the electric lighting would be turned off, and the subject would have to adjust the shading device(s) in such a way that the visual scene from her/his desk is at the BCD, a common discomfort glare borderline [Luckiesh et al. 1949].

However, this possibility was ruled out for different reasons:

- The subjects of a laboratory study [Wienold 2009a] were observed to readjust the blinds a few minutes after they made the first adjustment when asked to set the blinds to a comfortable level. It is assumed that the subjects do not consider the adaptation time, namely the time taken by the eyes to adjust to new lighting conditions. Therefore, by letting the subject set the shading device(s) to the BCD, it could not have been assured that the situation stays discomforting when the subject's eyes adapt to it.
- Because the study took place in real office buildings, most of the subjects took part in the study while other office workers were working around them. In those conditions, asking a subject to move the shading device(s) to find the BCD would have been impractical and annoying for both the subject and the other workers, especially because visual perceptions are spatially dependent, and it might have required the subject several back and forth to the window and with the device(s) to find the right position.
- In several cases, the office environment was such that a discomforting visual scene could not be created. By applying the suggested protocol (i.e., subjects setting the shading device(s) to the BCD), these visual scenes should have been excluded from the sample. Conversely, if a discomforting visual scene could not be created when applying the former protocol, the

subject could just rate the scene as comfortable and the data was not lost.

An alternative of the original protocol was finally adopted: two discomfort glare evaluations would be collected, with the first one made in the lighting conditions in which the subject was working before the session.

As such, a subjective assessment and measurement of the original visual scene would be collected at the beginning of the session. On the one hand, this would alleviate the imposition of lighting modification for the subject, by taking into account her/his working conditions and familiarizing her/him with the study. On the other hand, this would serve as training for the subject for the second subjective assessment.

Just after the first evaluation, the lighting conditions would be modified to maximize the potential for visual discomfort, and the subject would adapt to it while answering the part of the questionnaire where general information is collected. The second subjective assessment and measurement of the visual scene would then be collected, at the end of the session.

Besides this major change in the protocol of the study, the feedback of the subjects from the pilot study also led to small modifications in the questionnaire, such as the use of pictogram scales to assess the emotional, fatigue, and physical states of the subjects instead of numerical rating scales, or the addition of the option Ambidextrous to the handedness question. Furthermore, a short video would be used to give the explanations to the subject at the beginning of the session, in order to ensure that each subject receives the same information.

Finally, since the lighting levels measured during the pilot study were very low, the choice of office buildings for the study was made based primarily on the optimization of daylighting inside the buildings. Stricter selection criteria were also defined, as detailed in Subsection 4.1.4, to ensure that the lighting conditions maximized the potential for visual discomfort at the time of the session. There-

fore, only office workers having their desk located next to a west-, south-(/north- for Chile), or east-oriented window could participate in the study, and the study would only be conducted under sunny conditions.

4.1.10 Procedure

As a result of the decisions made in the previous subsections and of the pilot study learnings, the procedure of the study to determine the influence of the socio-environmental context on discomfort glare perception was defined. The timeline of one session of the study is summarized in Figure 4.13.

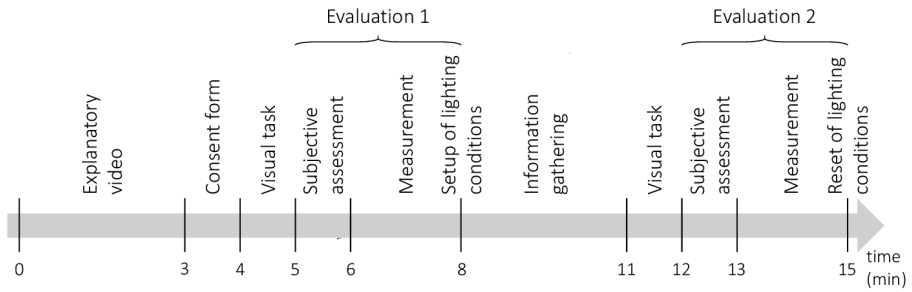


Figure 4.13: Timeline of the protocol of the field study for one subject

As a reminder, a cross-sectional, between-subjects study was conducted in real office buildings in Chile, Belgium, Japan, and Switzerland, in order to study the influence of the socio-environmental context of a subject on her/his discomfort glare perception from daylight. In each investigated socio-environmental context (CL, BE, JP, CH), at least 60 office workers, of which the office desk met the predetermined selection criteria, took part in the study. The study was conducted around the summer months in each country, to maximize the occurrence of clear sky days, and to avoid seasonal bias in subjects' answers.

The subjects were recruited according to their availability on the day of the study in their office building, during work hours, and no compensation was given for their participation. One session lasted around 15 minutes, and the investigator was present during

the entire session for each subject to ensure that the protocol was always the same. It unfolded as presented in Figure 4.13.

In the first place, when entering an office room, the investigator asked the office workers whether they would be willing to take part in a study on comfort in working environments. It was decided not to tell directly to the subjects that the object of the study was their discomfort glare perception, so that the subjects' attention is not focused on it. When an office worker agreed to give 15 minutes of her/his time for the study, he/she was shown a three-minute **explanatory video**.

The video was recorded in each of the four languages, namely French, English, Spanish, and English with Japanese subtitles. It described the general procedure of the session, including the consent form, the questionnaire, and the measurements, and what was expected from the subject. The video was used to ensure that the exact same information was given to each subject, and so that the subjects could visualize how the measurements would be taken. The English transcript of the video is available in Appendix F.

While the subject was watching the video, the investigator recorded the date and time of the beginning of the session, and set the luxmeter on the subject's desk to start collecting horizontal illuminance values every 20 seconds. These automated measurements were required to determine the stability of the lighting conditions, as explained in Subsection 4.1.7.

After the video, the subject first gave her/his email address to be sent the questionnaire, then read and signed the **consent form**. This consent form was required for the ethical agreement delivered by the Comité d'Ethique Hospitalo-Facultaire Saint-Luc UCL (ref: PEX-SUDGICA-01). While the subject was reading the form, the investigator placed two mid-range gray targets in the FOV, on which the spot luminance values could be measured.

The subject started answering the questionnaire, which began with the **visual task**. After performing the three series of Landolt rings, the subject was directly led to the first discomfort glare evaluation. The visual scene evaluated was the one in which the subject was

working before the session. The discomfort glare evaluation consisted of a subjective assessment of the visual scene followed by the measurement of the scene.

The **subjective assessment** started with a general question about satisfaction with the lighting conditions, and an OEQ if the conditions were not totally satisfying. Two different glare rating scales (A and B), or three (A, B, and C) for the Japanese and Swiss socio-environmental contexts, were then used to ask directly about discomfort glare perception. When the subjective assessment was done, the subject was asked to stand back from the desk and stay behind the equipment during the measurement.

The **measurement** of the visual scene was done via a luminance map generated through HDR photography. Discomfort glare metric values of the scene, as well as other photometric quantities, could be outputted from the luminance map thereafter. For the HDR photography technique, a sequence of LDR images of the visual scene, two spot luminance measurements, and two vertical illuminance measurements were needed. These were measured just after the subjective assessment at the same place of the subject's eyes.

Once the first discomfort glare evaluation was done, the subject was invited to take her/his seat again and proceed with the questionnaire, while the investigator **modified the lighting conditions** by turning off the electric lighting if on, and opening the shading device(s). The investigator also collected measurements of the air temperature and the relative humidity.

The subject adapted to the new lighting conditions as he/she was answering the part of the questionnaire where **information about the socio-environmental context and other studied factors were gathered**. These questions were followed by a second **visual task**, similar to the first one with three series of Landolt rings ensuring that the subject's FOV was focused on the screen.

The second visual task preceded the second discomfort glare evaluation, made in the modified lighting conditions to optimize the potential for visual discomfort. The second discomfort glare evaluation was similar to the first one, with a **subjective assessment**

made through the questionnaire, followed by a **measurement** of the visual scene.

The session ended with the measurement of the visual scene in the modified lighting conditions. At the end, the investigator reset the shading device(s) in their original position before leaving the room and starting a new session in the next office. This procedure was repeated for the 28 office buildings investigated in the 4 socio-environmental contexts between March 2017 and July 2018. Table 4.4 summarizes the dependent, independent, and moderating variables of the study.

Type of variable	Variable
Independent	Subjective assessment of discomfort glare from daylight
Dependent	Socio-environmental context of the subject
	Measurement of discomfort glare from daylight
Moderating	Gender of the subject
	Age of the subject
	Chronotype of the subject
	Self-assessed glare sensitivity of the subject
	Optical correction of the subject
	Iris pigmentation of the subject
	Physical state of the subject
	Emotional state of the subject
	Fatigue of the subject
	Caffeine ingestion of the subject
	Attractiveness of the view through the window
	Air temperature
	Time of the day
	Experimental biases

Table 4.4: Summary of the variables of interest in this research

4.2 Data Processing

In the previous section, the study design to investigate the influence of the socio-environmental context of a subject on discomfort glare perception was detailed. The collected raw data from the study consists in:

- a signed consent form for each subject
- tables containing the automated measurements of the horizontal illuminance on each subject's desk
- tables containing identification information (country, city, subject, date, time) and measurements taken manually in situ (vertical illuminance at eye level, spot luminance, air temperature, and relative humidity) during each session
- tables containing the answers to the online questionnaire for each subject
- a sequence of LDR images for each discomfort glare evaluation

Before running analyses, the data needs to be processed and cleansed to keep only appropriate and reliable information in the most relevant format. This section describes the processing steps applied to the raw data.

4.2.1 Anonymization

In accordance with the law of 8 December 1992 on protection of privacy in relation to processing of data of a personal nature, and as required by the Comité d'Ethique Hospitalo-Facultaire Saint-Luc UCL that assessed the protocol of this study (ref: PEX-SUDGICA-01), the raw data were anonymized so that none of the subjects could be recognized.

A specific Identifier (ID) was defined for each discomfort glare evaluation -and not for each subject since they each did two evaluations- in the following form (Figure 4.14).

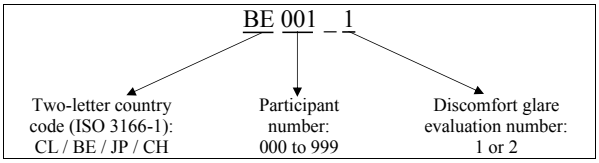


Figure 4.14: ID format defined for each discomfort glare evaluation collected during the field study

4.2.2 Analysis of Horizontal Illuminance

During each session (except for those of the Chilean group), measurements of horizontal illuminance were collected automatically every 20 seconds on the subject's desk to monitor the stability of the lighting conditions throughout the entire session. Since there was no interruption between the first and second discomfort glare evaluations, the first necessity was to split the series of measurements when the change in the lighting conditions was made. Then, each of the two series of measurements had to be assigned to the corresponding discomfort glare evaluation (1 or 2). The maximum deviation in horizontal illuminance was calculated for each discomfort glare evaluation according to Equation 4.2.

$$E_{h,max.dev.} = \begin{cases} 100 \cdot \dfrac{\min(E_h) - \mathrm{med}(E_h)}{\mathrm{med}(E_h)}, \\ \quad \text{if } \mid \min(E_h) - \mathrm{med}(E_h) \mid > (\max(E_h) - \mathrm{med}(E_h)) \\ 100 \cdot \dfrac{\max(E_h) - \mathrm{med}(E_h)}{\mathrm{med}(E_h)}, \\ \quad \text{if } \mid \min(E_h) - \mathrm{med}(E_h) \mid < (\max(E_h) - \mathrm{med}(E_h)) \end{cases} \tag{4.2}$$

where:

$E_{h,max.dev.}$ is the maximum deviation in horizontal illuminance [%]

$\mathrm{med}(E_h)$ is the median horizontal illuminance [lux]

$\min(E_h)$ is the minimum horizontal illuminance [lux]

$\max(E_h)$ is the maximum horizontal illuminance [lux]

4.2.3 Analysis of Open-Ended Questions

The subjective assessment of discomfort glare as well as other information was collected from the subject through a questionnaire that was completed online on their computer. The questionnaire, designed through LimeSurvey software, was sent to the subject's email address at the beginning of the session.

The subjects of the Chilean group answered the Spanish version of the questionnaire; those of the Belgian group answered the French version; those of the Japanese group the Japanese version; and those of the Swiss group either the French or the English version.

All the answers were directly stored on a server of UCLouvain. At the end of the study, the answers were gathered by the investigator in one large table and translated into English, except for the OEQ answers which were kept in their original language.

As a reminder of the questionnaire, the subjective assessment of the visual scene started with the question:

At the moment, are you satisfied with the lighting conditions in your office?

- ○ Unsatisfied
- ○ Rather unsatisfied
- ○ Rather satisfied
- ○ Satisfied

If the subject did not answer that he/she was Satisfied, then he/she was asked why through the OEQ:

Which element(s) bother(s) you in the current lighting conditions?

A systematic approach was adopted to categorize the answers to the OEQ according to two variables, i.e., the variable "What" to answer the question "What is bothering in the current lighting conditions?", and the variable "Why" to answer the question "Why is it bothering in the current lighting conditions?".

Five categories were defined for the variable "What" so that all subjects' answers could be categorized. These categories are:

- 0 if the subject was satisfied, did not mention a specific element, mentioned an element that bothered him/her at times but not at that specific moment, or mentioned an element not relevant to the lighting conditions (e.g., the view, the heat);
- Electric lighting if the subject mentioned an element related to the electric lighting that bothered him/her at that specific moment;
- Computer screen if the subject mentioned an element related to the computer screen that bothered him/her at that specific moment;
- Daylighting if the subject mentioned an element related to daylight that bothered him/her at that specific moment;
- General lighting if the subject was mentioning an element related to the general lighting that bothered him/her at that specific moment.

The variable "Why" was found to be dependent on the variable "What". All answers categorized as 0 for the variable "What" were also categorized as 0 for the variable "Why", regardless of whether the subject was satisfied, complaining about the view or the broken blinds. This information was disregarded since it could not be used in the following analyses. Only the answers related to the current situation that was evaluated could be investigated in the analyses.

The answers mentioning an issue with the general lighting, categorized as General lighting for the variable "What", all indicated too lighting levels that were too low, and which did not ensure good visibility. These answers were categorized as Dim lighting for the variable "Why".

The answers categorized as Computer screen for the variable "What" could be categorized according to three categories for the variable "Why"; either the screen was too bright, categorized as Brightness, or there were reflections on the screen, categorized as Reflections, or

the answer did not mention a reason for the element to be bothering (e.g. "*écran*"), categorized as NA.

Lastly, the answers categorized as Electric lighting and Daylighting for the variable "What" could be referring to four main reasons of bother. The first reason, which in the case of daylight is of great interest for this research, was Discomfort glare, which gathered all disturbances related to bright windows or lamps, high contrasts, etc. The second reason why the electric or daylighting could be bothering was categorized as Type, and included disturbances due to color, distribution, flicker, stability, etc. Several answers also mentioned a lack of daylight, which were then categorized as Daylighting for the variable "What" and as Insufficiency for the variable "Why". At last, some answers did not detail why the electric lighting was bothering and were categorized as NA. The number of answers in each category is shown in Figure 4.15.

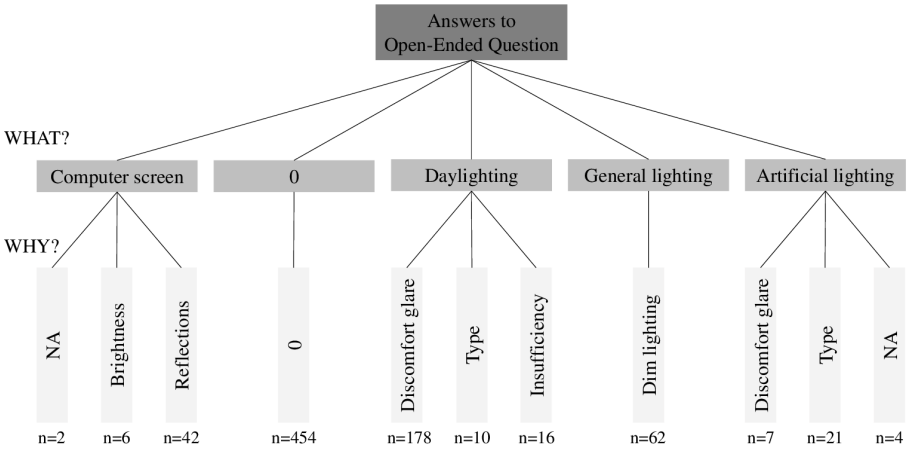


Figure 4.15: Result of the categorization of the answers to the OEQ according to the "What" and "Why" variables

In total, 178 out of 802 (22%) answers to the OEQ assessing the visual scene were categorized as discomfort glare from daylight, by being categorized simultaneously as Daylighting and Discomfort glare. A binary variable expressing daylight discomfort glare, defined as the "Glare report", could then be generated from the OEQ analysis, with 0 or No glare report meaning that there was no day-

light discomfort glare report, and 1 or Glare report meaning that there was a daylight discomfort glare report.

The answers to the OEQ in the original language are all available in Appendix A, together with the categorization of these answers for the variables "What" and "Why".

4.2.4 Analysis of Visual Scenes

As described in Subsection 4.1.10, two sequences of LDR images were captured during each session; the first one in the original lighting conditions in which the subject was initially working, and the second one in the modified lighting conditions. Before being used to generate the luminance maps, these images were visually analyzed to retrieve useful information regarding the visual scenes evaluated, which was not recorded at the time of the study. The information retrieved from each of the 802 LDR sequences consisted in:

- the presence of a window in the FOV

  A few subjects had unfortunately the window in their back. The presence of a window in the FOV of the image was recorded and stored as a binary variable, with 0 meaning that the window was not in the FOV, like in Figure 4.16.



Figure 4.16: Visual scene of the field study with no window in the FOV

- the approximate distance from the window

Some subjects were located relatively far from the window. This information was extracted from the images by visually estimating, for all visual scenes with a window, whether the subject distance from that window was approximately longer than five meters, like in Figure 4.17. This information was stored as a binary variable, with 0 meaning that the approximate distance from the window is longer than five meters.



Figure 4.17: Visual scene of the field study with a window far from the subject

- the lighting type of the visual scene

  The original lighting conditions could be different for each subject, as well as the modified lighting conditions since it was not always possible to turn off the electric lighting for instance. The information retrieved from one of the LDR images collected for each discomfort glare evaluation indicates whether the lighting type of the visual scene evaluated was daylighting only (D), electric lighting only (L), or both daylighting and electric lighting (DL), like in Figure 4.18.

  In a few cases where the window was in the back of the subject, it was not possible to determine from the image whether or not the shading device was open, or whether the scene was partially daylit. These visual scenes were categorized as (NA).

- the shading device state in the visual scene

  For the visual scenes with a window, the shading device of that window, when there was one, could not always be manipulated.



Figure 4.18: Visual scene of the field study with both daylighting and electric lighting

Therefore, some shading devices had to stay closed during the entire session, while others were open. The information about the shading device state was retrieved from each image. A categorical variable was defined to detail whether the shading device was fully open (O), like in Figure 4.19, fully closed (C), or neither fully open nor fully closed (M). For a few visual scenes, the information about the shading device state could not be extracted. These scenes were classified as (NA) since the window was either not in the FOV or too far from the subject's desk.



Figure 4.19: Visual scene of the field study with fully open shading device

- the lighting conditions modification

Each subject evaluated two visual scenes; one in the original lighting conditions, and one in modified lighting conditions. In some cases, no modification could be brought to the original lighting conditions due to a broken shading device, a lamp that could not be turned off, or when the conditions were already maximizing daylight. The subjects were thus evaluating twice the same visual scene. The information about the lighting conditions modification was retrieved from the two previous elements (the lighting type of the visual scene, and the shading device state in the visual scene). A categorical variable was defined to detail whether the visual scene could not be modified (N), whether only the electric lighting could be modified (L), whether only the shading device could be modified (S), or whether both the electric lighting and the shading device could be modified (SL), such as between Figures 4.18 and 4.19.

4.2.5 Analysis of Luminance Maps

Luminance maps of each subject's FOV were generated to calculate the discomfort glare metric values corresponding to the visual scenes evaluated. As described in Subsection 4.1.7, luminance maps, of which each pixel represents the luminance of the corresponding portion of the captured FOV, are generated through HDR photography and a half automatic half manual calibration process [Pierson et al. 2019a].

Although this calibration process makes it possible to produce luminance maps with good photometric accuracy and without expensive equipment nor specific coding skills, the process is tedious and error-prone since it involves multiple sensitive steps. Therefore, it is essential to check the validity of the calibrated 180° HDR images.

This validity check is done against the measured vertical illuminance values. The comparison between the HDR-derived vertical illuminance value and the mean of the measured vertical illuminance values is a way of checking the luminous balance to ensure that the total lighting energy embodied in the luminance map is equivalent to the total lighting energy reaching the illuminance sensor placed

next to the lens at the time of the study. The HDR-derived vertical illuminance values were calculated with the evalglare program [Wienold et al. 2006] and compared to the mean of the two vertical illuminance values measured in the scene. The error between the HDR-derived and measured vertical illuminance was calculated according to Equation 4.3.

$$\varepsilon_{E_v} = \frac{E_{v,HDR} - E_{v,measured}}{E_{v,measured}} \cdot 100 \tag{4.3}$$

where:

ε_{E_v} is the error in vertical illuminance [%]

$E_{v,HDR}$ is the HDR-derived vertical illuminance [lux]

$E_{v,measured}$ is the mean of the measured vertical illuminance [lux]

If the error between the two values was larger than 5%, the photometric adjustment was applied a second time using the second target. It could indeed happen that one of the two spot luminance values measured in the scene was not accurate enough to be used for calibration, as these have been shown to produce errors up to around 10% [Inanici 2006; Cai et al. 2011]. After the second manual photometric adjustment, the HDR-derived vertical illuminance was calculated again with evalglare, and the comparison was done a second time through the evaluation of the error. The luminance map producing the largest error was discarded.

In 14 cases, the HDR-derived vertical illuminance stayed much lower than the measured vertical illuminance regardless of the target used for the photometric adjustment. A visual analysis of these HDR images showed that the sun was directly visible in the FOV for all the scenes. Although an ND filter should have been used for all these scenes, it was only applied for nine of them. In any case, the 14 HDR images were exhibiting pixel overflow.

Pixel overflow, also referred to as sensor blooming, consists of a pixel reaching its limited charge capacity, propagating the extra charge to surrounding pixels. ND filters should be used in situations of pixel overflow since they reduce the amount of light hitting the

sensor, permitting it to capture larger luminance values. It was decided to correct the 14 HDR images by using the pixel overflow correction option in the evalglare program. This option requires as input the HDR image to correct, as well as the corresponding measured vertical illuminance and the area in the HDR image where the pixel overflow occurs. The luminance of the area with pixel overflow is adjusted in such a way that the HDR-derived vertical illuminance matches the measured one.

In addition, the ND filter was applied for another four cases in addition to the nine previously mentioned, and no pixel overflow was detected.

4.2.6 Discomfort Glare Metrics Evaluation

The discomfort glare metric values corresponding to a visual scene can be calculated from the luminance map of the scene through the evalglare program. Evalglare is a Radiance-based program developed by J. Wienold as part of a larger glare study with J. Christoffersen [Wienold et al. 2006]. First, evalglare runs an algorithm on a 180° luminance map to detect glare sources, if any. Then, it determines the characteristics of these glare sources, as well as general lighting quantities before calculating the discomfort glare metric values.

In Subsection 4.2.5, the luminance maps corresponding to the 802 visual scenes have been generated. The glare stimuli produced by these scenes are represented via several discomfort glare metric values, which are calculated as detailed in this subsection.

Selection of the Discomfort Glare Metrics Based on the Literature

As mentioned in Section 2.1, there exist at present more than 20 daylight discomfort glare metrics [Wienold et al. 2019]. Although it is not recommended to use all of them for the statistical analyses, it would not be representative to only use one. Several metrics have to be chosen, but the more discomfort glare metrics that are tested with the same data set, the higher the chances are to produce a

Type I error, i.e., to incorrectly reject a null hypothesis [Wasserman 2003].

To account for this issue of multiple testing, a correction, such as the Bonferroni one (Subsection 4.5.1), can be applied to the significance level. But when there are many significance tests, namely many discomfort glare metrics to test, the Bonferroni correction becomes very strict and increases the risk of a Type II error [Field et al. 2012]. It is therefore recommended to restrict the number of multiple significance tests, and thus the number of metrics. A reduced number of daylight discomfort glare metrics would have to be selected from the list of 22 established in [Wienold et al. 2019]. This selection would be based not only on the performance and robustness of the metrics, but also on their popularity in the research field.

First, the metrics not included in the top ten in terms of performance and robustness based on the cross-validation study in [Wienold et al. 2019] were removed. From the reduced list (11 metrics due to a tie), the most well-established metrics in the glare research community were selected, namely the DGP [Wienold et al. 2006], the PGSV [Iwata et al. 2010; Tokura et al. 1996], the CGI [CIE 1995; Einhorn 1979], the DGI [Hopkinson 1972; Chauvel et al. 1982], and its updated version, the DGI_{mod} [Fisekis et al. 2003].

Since these were mainly metrics representative of contrast glare, the three most highly ranked metrics representative of saturation glare were added to this list, which included the E_v [Velds 2000; Wienold et al. 2006], the $PGSV_{sat}$ [Iwata et al. 2010], and the L_{mean} [Van Den Wymelenberg et al. 2014]. The eight metrics that have been selected for the statistical analyses and that have to be calculated from the luminance maps are:

- the Daylight Glare Probability (Equation 2.13)
- the Predicted Glare Sensation Vote (Equation 2.8)
- the CIE Glare Index (Equation 2.5)
- the Daylight Glare Index (Equation 2.7)
- the Modified Daylight Glare Index (Equation 2.11)

- the Vertical Illuminance (Equation 2.9)
- the Saturated Predicted Glare Sensation Vote (Equation 2.8)
- the Mean Luminance (Equation 2.15)

This list of eight metrics is believed to be representative of daylight discomfort glare metrics nowadays, since it includes the most robust and best performing metrics [Wienold et al. 2019]. Furthermore, the list ensures an equity between contrast-based metrics (CGI, DGI, DGI_{mod}) and saturation-based metrics (E_v, L_{mean}, $PGSV_{sat}$), with also two metrics representative of both discomfort glare types (DGP, PGSV).

Additional Information for Metrics Evaluation

As previously mentioned, the calculation of the discomfort glare metric values is done by evalglare. Evalglare algorithm detects the glare sources in the luminance map before determining the characteristics of these glare sources, such as their mean luminance, solid angle, and position index, as well as other lighting quantities, such as the vertical illuminance or the background luminance. However, two variables required for the calculation of the eight selected metrics cannot be determined by evalglare solely from the luminance map.

The first variable is the mean luminance of the window, which is required for the calculation of the PGSV value. Evalglare cannot automatically detect windows in luminance maps. Therefore, to determine the mean luminance of a window, evaglare needs to be told where the window area is in the luminance map. This is done by inputting, besides the original luminance map, a masked HDR image. The masked HDR image contains the same visual scene as the luminance map, but all the pixels not included in the window area have been set to black (Figure 4.20).

To create such a masked HDR image, a luminance map was first converted with the ra_ppm program of Radiance [Ward 1987] from a .hdr image into a .ppm image that preserves the calibrated pixel values. .ppm images can be visualized and edited in different image



Figure 4.20: Masked HDR image of a subject's FOV showing only the window in the FOV

editing software, such as Gimp. In a second step, the window area was delimited in the .ppm image, with the limits set in the middle of the window frame and the shadings included in the area. All pixels outside of this area were then set to black ($R, G, B = 0, 0, 0$). The last step consisted in converting back with ra_ppm the .ppm image into a .hdr image supported by evalglare. This manipulation was executed on each of the 802 luminance maps having a window in the FOV, namely 702 luminance maps (88%).

The second variable that cannot be retrieved directly from the luminance map is the mean luminance of the task area. The mean luminance of the task area is required, on the one hand, for the glare source detection algorithm, and on the other hand, for the conditional equation in the PGSV formula. The task area is defined as the area within which the visual task is carried out [CEN 2011b]. For this study, the task area includes therefore mainly the computer screen on which the subject was completing the questionnaire, and partly the keyboard.

The exact location of this task area changes slightly between the luminance maps, and should be communicated to evalglare. Evalglare algorithm uses by default a circular task area, defined by center coordinates and an opening angle, in order to determine the mean

luminance of this area. Moreover, an HDR image can be outputted from evalglare where this task area is highlighted in blue (Figure 4.21).

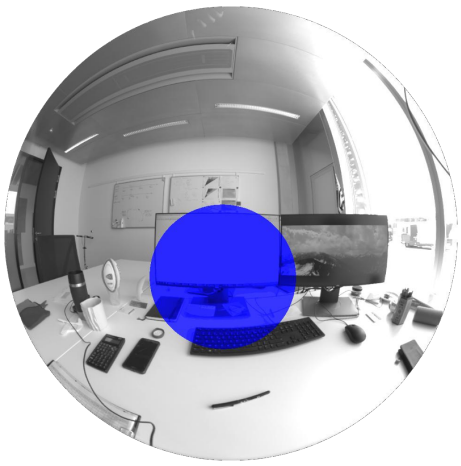


Figure 4.21: HDR image of a subject's FOV with the task area highlighted in blue

Besides being used to locate the window area, the .ppm images derived from the luminance maps were visually analyzed in Gimp so that the center coordinates of the task area can be defined with the "pointer" command. Attention was paid to the reference system origin, and the coordinates were stored in a table. A fixed opening angle was used for the size of the task area, and was set to 0.5 rad, namely 30° (aperture of 60°), to correspond to the ergorama [Andersen 2004].

A first run of evalglare was executed on the luminance maps to output checkfiles, namely HDR images with the highlighted task area (Figure 4.21). The task area position was examined in each checkfile, and the center coordinates were modified when necessary. Moreover, exceptions were made for the definition of the task area center when the subject's computer screen had switched to standby mode before the measurements were taken. Since the mean luminance of a task area centered on a black screen would have been too low to be used as a glare source luminance threshold, the task area was moved mainly around the keyboard.

Calculation of Discomfort Glare Metric Values with Evalglare

This subsection includes amended parts of an open-access study article published in Buildings [Pierson et al. 2018a], which is reproduced in Appendix I.

As previously mentioned, evalglare was used to calculate the discomfort glare metric values corresponding to the 802 visual scenes. The algorithm first detects the glare sources in the FOV of the luminance map. Up to now, the definition of a glare source is still ambiguous [Pierson et al. 2018b], and there is no universal method of identifying one. The most common methods are the ones implemented in evalglare, namely the factor method, the threshold method, and the task area method, which are described below.

- The algorithm of the factor method detects in the 180° luminance map all pixels having a luminance value higher than the mean luminance of the luminance map multiplied by a certain factor (Equation 4.4). The pixels that meet this rule form the glare sources.

$$\text{If } L_i \geqslant K_1 \cdot L_{mean}, \text{ then } i \in Z_G \tag{4.4}$$

- The algorithm of the threshold method detects in the 180° luminance map all pixels having a luminance value higher than a certain threshold (Equation 4.5). The pixels that meet this rule form the glare sources.

$$\text{If } L_i \geqslant L, \text{ then } i \in Z_G \tag{4.5}$$

- The algorithm of the task area method detects in the 180° luminance map all pixels having a luminance value higher than the mean luminance of a defined task area in the luminance map multiplied by a certain factor (Equation 4.6). This method requires the prior definition of a task area. The pixels that meet this rule form the glare sources.

$$\text{If } L_i \geqslant K_2 \cdot L_t, \text{ then } i \in Z_G \tag{4.6}$$

in these equations:

L_i is the luminance of the pixel i [cd/m^2]

$K_{1,2}$ are multiplying parameters [-]

L_{mean} is the mean luminance of the 180° luminance map containing the FOV [cd/m^2]

L is a luminance threshold [cd/m^2]

L_t is the mean luminance of the task area [cd/m^2]

Z_G gathers all the pixels forming the glare sources

The results of a study on evalglare parameters [Pierson et al. 2018a] suggest that the choice of the glare source detection method should be done considering the type of discomfort glare that is most likely to occur in the visual scene. The task area method should be preferred for contrast glare scenes, and the threshold or task area method for saturation glare scenes. Furthermore, a threshold of 2000 cd/m^2 for the threshold method and a multiplying factor of 4 or 5 for the task area method offer the best results.

Since only desk positions located close to a window were investigated during the field study, the expected type of discomfort glare was mainly saturation glare from daylight. The task area method with a factor 5 was chosen as the principal glare source detection method for the evalglare algorithm. The other parameters required by evalglare for glare source detection were also set according to the results of the study:

- the search radius, namely the distance within which two glaring pixels are included in the same glare source, was set as its default value, 0.2 rad
- the background luminance was defined (Equation 4.7) according to CIE [CIE 1995]

$$L_b = \frac{E_v}{\pi} \tag{4.7}$$

- remaining parameters such as the position index or the smoothing option were left to their default values

With the predefined center coordinates and opening angle of the task area, evalglare algorithm (with the task area 5 method) ran on the 802 luminance maps through an R script in Linux automating the process. A checkfile highlighting the task area in blue and the glare sources in yellow was generated for each luminance map (Figure 4.22), in addition to the data containing the characteristics of the detected glare sources and several discomfort glare metric values.

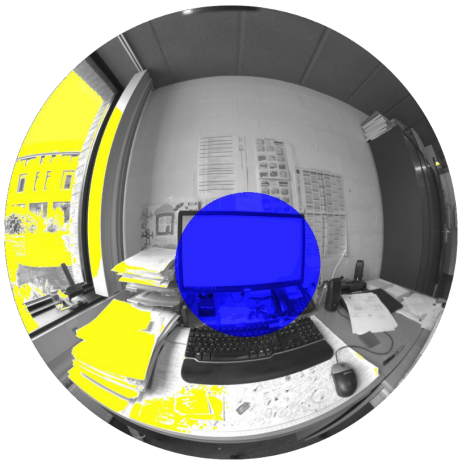


Figure 4.22: Checkfile generated by evalglare (task area 5 method) from an HDR image of a subject's FOV highlighting the detected glare sources in yellow and the task area in blue

The conclusion of the study on evalglare parameters [Pierson et al. 2018a] recommends to examine visually the glare sources detected in the checkfile in order to verify that the detection is made reasonably. The visual check is necessary to ensure that the algorithm does not over- or under-detect glare sources.

With the task area method, over- or under-detection of glare sources could occur when the mean luminance of the task area is very low (e.g., when there is a large dark surface such as a standby computer screen included in the task area), or very high (e.g., when a glare source is partially included in the task area). In these cases, the task area method is not relevant, and the threshold method with a threshold of 2000 cd/m^2 should be used. A thorough visual analysis of the 802 checkfiles led to a change of the glare source detection

method for 137 luminance maps, mainly due to the partial inclusion of a glare source in the task area, like in Figure (4.23).

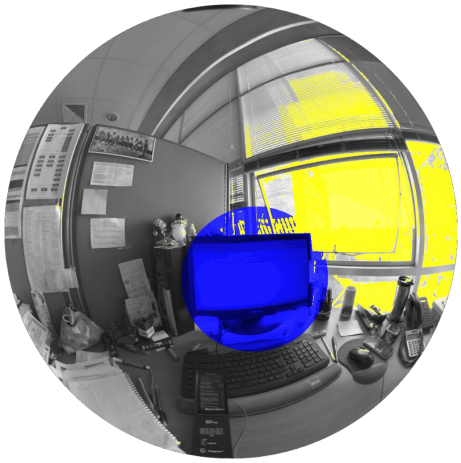


Figure 4.23: Checkfile generated by evalglare (task area 5 method) from an HDR image of a subject's FOV showing a glare source (in yellow) partially included in the task area (in blue)

Evalglare algorithm with the threshold method and a threshold value of 2000 cd/m^2 ran on the 137 luminance maps through an R script in Linux automating the process. A checkfile highlighting the detected glare sources (Figure 4.24) was generated for each luminance map, in addition to the data containing the characteristics of the detected glare sources and several discomfort glare metric values. A visual check of these 137 checkfiles was also executed, to ensure that there was no unreasonable over- or under-detection of glare sources. The glare source detection method used to calculate the discomfort glare metric values of each visual scene was stored in a table.

In the data produced by the execution of evalglare algorithm using the two different glare source detection methods, the values of six (DGP, CGI, DGI, DGI$_{mod}$, PGSV$_{sat}$, L$_{mean}$) out of the eight selected discomfort glare metrics were calculated.

As previously mentioned, the calculation of the PGSV value requires the mean luminance of the window. To determine this value, evalglare needs the previously generated masked HDR image as an

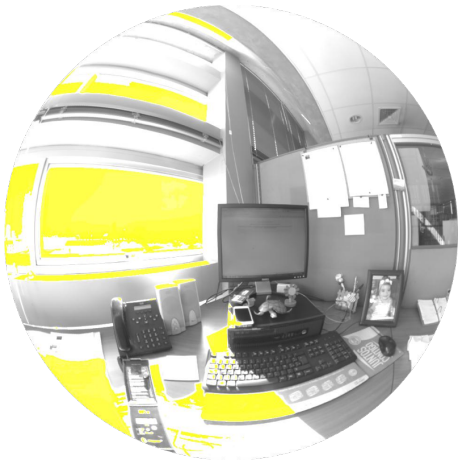


Figure 4.24: Checkfile generated by evalglare (threshold 2000 method) from an HDR image of a subject's FOV highlighting the detected glare sources in yellow

additional input so that the window area is known. A specific run of evalglare algorithm with the masked HDR image had to be executed to calculate the PGSV value. Furthermore, since the PGSV metric considers that the only glare source in a daylit FOV is the window and does not rely on the detection of other glare sources, the glare source detection method in evalglare was irrelevant. The specific run of evalglare was executed for the 802 visual scenes and automated through an R script in Linux.

Moreover, since E_v was directly measured by a luxmeter placed next to the camera lens, the measured value was used in the analyses instead of the HDR-derived value. As much less processing is required, the directly measured E_v is believed to be less error-prone than the HDR-derived one.

The values of the eight discomfort glare metrics corresponding to each of the 802 visual scenes and calculated with the relevant glare source detection method were stored in a table.

After all the processing steps described in this section, the information required for the analyses of the socio-environmental context influence on discomfort glare perception was available in the most relevant format.

4.3 Data Cleansing

By conducting the study described in Section 4.1, 802 discomfort glare evaluations made by 401 subjects were collected, of which 85 are from Chile (21%), 86 are from Belgium (21%), 119 are from Japan (30%), and 111 are from Switzerland (28%). The collected raw data has been processed as described in Section 4.2 to be available in a convenient format to be analyzed. The objective of this section is to cleanse the processed data.

Data cleansing consists in ensuring that all data points are appropriate, by filtering out those that do not meet the eligibility criteria, and reliable, by removing those that are incorrect because they contain missing, aberrant or extreme values [Tuffery 2011]. The objective of data cleansing is therefore to remove the data that does not allow the researchers to adequately answer the research question.

As explained in Section 4.1, data selection criteria were previously defined to be applied during data collection. For instance, data collection could only take place under clear sky conditions; people having their desk located next to a north-oriented (or south-oriented for the Chilean group) window could not participate in the study; only people having their desk located next to a window could participate in the study; etc. The application of these criteria required flexibility during the data collection phase, which was not possible to provide in all socio-environmental contexts. Therefore, some subjects were surveyed, although the selection criteria were not met.

For this reason, data cleansing rules had to be established to filter out inappropriate or unreliable data points a posteriori and ensure data quality. Besides the obvious rule for the uniqueness of subjects' evaluation (Subsection 4.3.1), the ten other rules are concerned with the stability of the lighting conditions, the accuracy of the measures, and the comparability of the visual scenes.

4.3.1 Uniqueness of Subjects' Evaluation

The field study was designed as a between-subjects study (Subsection 4.1.1), meaning that different groups of subjects were surveyed for the different socio-environmental groups. The between-subjects study design implies that only one discomfort glare evaluation per subject is used in the analyses. Since two discomfort glare evaluations were completed by each of the 401 subjects, one of the two had to be filtered out to ensure that the study does not mix the between-subjects and within-subjects study design types, which would have been confusing for the statistical analyses.

As explained in Subsection 4.1.9, the first discomfort glare evaluation, i.e., the one made in the lighting conditions in which the subject was working before the beginning of the session, was added in the procedure as training. Moreover, daylight was maximized in the second discomfort glare evaluation, providing a higher potential for daylight discomfort glare. For these reasons, an unmistakable rule establishes that the first discomfort glare evaluation made by each subject had to be filtered out.

Rule 0 *The discomfort glare evaluation has to be filtered out if it is the first evaluation made by the subject.*

Applying this rule obviously filtered out 50% of the full dataset (802 data points), i.e., 401 discomfort glare evaluations.

4.3.2 Stability of Lighting Conditions

As explained in Subsection 4.1.10, the measurement of the visual scene was done right after the subjective assessment of that scene. To ensure that the measured visual scene was the same as the subjectively assessed one, the lighting conditions had to remain stable during both steps. For instance, it could have happened that a cloud was passing in front of the sun during one of the two steps if the clear sky criterion had not been satisfied. This situation would have caused the visual scene, and thus the glare stimulus, to vary between the two steps, making that discomfort glare evaluation meaningless.

To verify the stability of the lighting conditions during each discomfort glare evaluation, which encompasses both the measurement and the subjective assessment, two rules have been defined based on the deviation in vertical illuminance and in horizontal illuminance:

Rule 1 *The discomfort glare evaluation has to be filtered out if the maximum deviation in horizontal illuminance is lower or equal to* -25% *or larger or equal to* 25%.

Rule 2 *The discomfort glare evaluation has to be filtered out if the deviation in vertical illuminance is lower or equal to* -15% *or larger or equal to* 15%.

The two rules were necessary to complement each other since both measures endured missing values. On the one hand, 191 missing values were found for the maximum deviation in horizontal illuminance. These were mainly due to the fact that the sensor for horizontal illuminance was not available for the study in Chile. On the other hand, 59 values were missing for the deviation in vertical illuminance, as one of the two vertical illuminance measures could not be properly recorded. The deviation in vertical illuminance was calculated according to Equation 4.8 and the maximum deviation in horizontal illuminance according to Equation 4.2, as described in Section 4.2.2.

$$E_{v,dev.} = 100 \cdot \frac{E_{v,2} - E_{v,1}}{E_{v,1}} \tag{4.8}$$

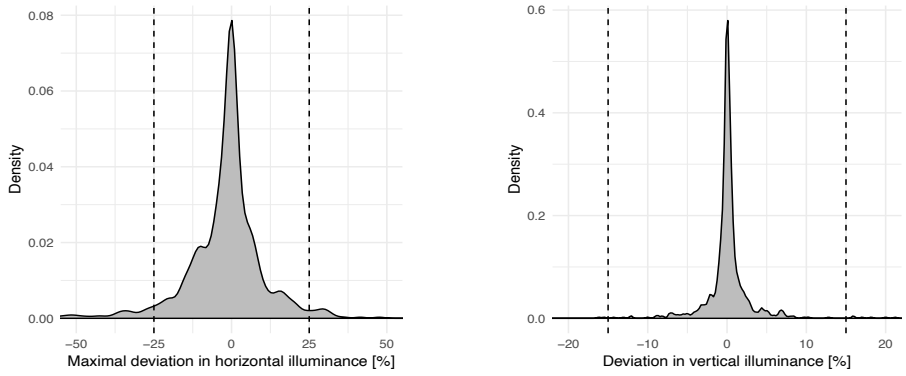
where:

$E_{v,dev.}$ is the deviation in vertical illuminance [%]

$E_{v,1}$ is the first measure (before the LDR sequence capture) of vertical illuminance [lux]

$E_{v,2}$ is the second measure (after the LDR sequence capture) of vertical illuminance [lux]

Up to now, there is no consensus on stability requirements for time series measurements in daylighting studies. Therefore, the acceptable percentage of deviation of the two rules were established based on the distribution of the deviation data (Figure 4.25).



(a) Maximum deviation in E_h

(b) Deviation in E_v

Figure 4.25: Density plots of E_v and E_h deviations during the field study; the vertical dashed lines are the thresholds for the rule of stability

An arbitrary threshold was set to ±25% for the maximum deviation in horizontal illuminance. Although this limit could be perceived as being lax, variations in horizontal illuminance on the desk were expected. The visual scene was indeed not static, since subjects had to walk away from their desk at some point, and the equipment had to be set up by the investigator. The upper limit therefore had to take into account that these actions could induce shadows. The application of a threshold of ±25% for the maximum deviation in horizontal illuminance caused the filtering out of 57 of the 802 discomfort glare evaluations (around 7%).

Figure 4.25b shows that the deviation in vertical illuminance between the measurement after the subjective assessment and the measurement before it was, in general, very low. A stricter threshold of ±15% was defined so that only the few outliers with a large deviation were filtered out. By applying the threshold of ±15% for the deviation in vertical illuminance, 15 of the 802 discomfort glare evaluations had to be removed (around 2%), of which 9 were already filtered out because of the criterion of maximum deviation in horizontal illuminance.

4.3.3 Accuracy of Measures

To ensure data quality and perform the analyses with reliable measures, the following rules aimed to filter out the discomfort glare evaluations that were not accurate.

On the one hand, the reliability of the measured discomfort glare stimulus, namely the discomfort glare metric values, had to be verified. The main source of error for the measured glare stimulus is from the luminance map. The discomfort glare metric values were indeed calculated based on the lighting conditions, which have been measured through the HDR photography technique. As mentioned in the study article [Pierson et al. 2019a], even when the complete calibration procedure is performed meticulously and a proper calibration factor is applied to each HDR image, some luminance maps generated through HDR photography have a significant error in vertical illuminance. Since an absolute error in vertical illuminance (calculated according to Equation 4.3) of less than 10% should be expected [Pierson et al. 2019a], the first rule to ensure accuracy of measures was defined accordingly:

Rule 3 *The discomfort glare evaluation has to be filtered out if the error in vertical illuminance of the luminance map is less than or equal to* -10% *or greater than or equal to* $+10\%$.

Twenty-one of the 802 discomfort glare evaluations (around 3%) had to be filtered out due to the application of this rule (Figure 4.26).

On the other hand, the reliability of the subjective assessment of the visual scene had to be verified. More generally, the questionnaire answers given by the subjects had to be inspected for response biases.

A response bias is a systematic tendency to respond to a range of questionnaire items on some basis other than the specific item content [Paulhus 1991]. The main response bias that was expected from this questionnaire was the acquiescence response bias, namely the tendency for subjects to agree or disagree with statements regardless of their content [Lavrakas 2008].

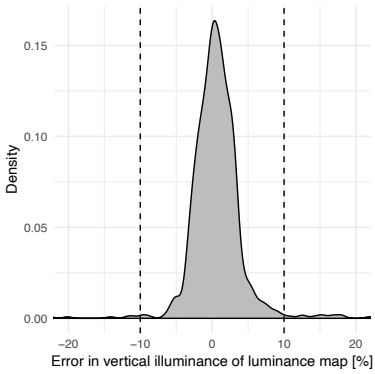


Figure 4.26: Density plots of the E_v errors of all the luminance maps collected during the field study; the vertical dashed lines are the thresholds for the rule of accuracy

To prevent such a bias, the number of questions was restricted to the minimum, in order not to induce fatigue that leads to answers given without considered thought. Moreover, the visual task that was required from the subjects through the questionnaire before making the subjective assessment of the visual scene was implemented in part as a method to detect the acquiescence response bias. If a subject was answering to the visual task without reading the question or considering carefully her/his answer, the bias would be reflected in the score of the visual task. An additional rule was therefore defined to ensure that subjects providing unreliable answers to the questionnaire were filtered out:

Rule 4 *The discomfort glare evaluation has to be filtered out if the score of one of the three series of the visual task is less than or equal to* 50%*.*

As described in Subsection 4.1.6, the visual task consisted in three series (one easy, one moderate, and one difficult) of six Landolt rings [Bach 1996] oriented in four different ways. The subject had to locate the orientation of the opening of each ring (Subsection 4.1.6). The difficulty was increased between each series by decreasing the size of the rings. Since people usually adapt the resolution of their screen to their visual acuity, the visual task was also adapted to the subject's visual acuity, which prevented the exclusion of subjects

with low visual acuity because of this rule.

The score of one series of the visual task was calculated according to Equation 4.9. By applying this second rule for accuracy of measures, 4 of the 802 discomfort glare evaluations (less than 1%) had to be filtered out.

$$S_x = 100 \cdot \frac{n_{correct}}{6} \tag{4.9}$$

where:

S_x is the score of the x series of the visual task [%]

$n_{correct}$ is the number of correctly located openings of Landolt rings [-]

4.3.4 Comparability of Visual Scenes

In order to compare discomfort glare perception between different subjects, the visual scenes assessed by these subjects have to be comparable. In Subsection 4.1.4, rules were established so that only offices offering a certain type of visual scenes were selected for the study. These rules aimed mainly at reducing the potential for contrast glare from daylight, and increasing that for saturation glare. Therefore, only people having their desk located next to a window could participate in the study. But as previously mentioned, the selection criteria were not always applicable. Three rules were thus defined to ensure that the discomfort glare evaluations for which there was no window in the near FOV are removed.

Rule 5 *The discomfort glare evaluation has to be filtered out if there is no window visible in the visual field of the luminance map.*

Rule 6 *The discomfort glare evaluation has to be filtered out if the window visible in the visual field of the luminance map has a solid angle less than or equal to* 0.01 *sr.*

Rule 7 *The discomfort glare evaluation has to be filtered out if the distance between the desk and the window, approximated from the HDR image, is greater than* 5 *m.*

By applying these three rules, 154 of the 802 discomfort glare evaluations (around 19%) had to be filtered out.

Even if the visual scenes were selected to maximize the potential for saturation glare from daylight and reduce that for contrast glare, two other types of visual discomfort could occur, namely discomfort glare from electric lighting and veiling glare. These types of visual discomfort have been described in Section 2.1.

On the one hand, these types of visual discomfort are not in the scope of this study, which focuses on daylight discomfort glare. On the other hand, these types of visual discomfort cannot be evaluated by daylight discomfort glare metrics.

In a recent study [Hirning et al. 2017], it was observed that including scenes assessed as discomforting due to screen glare or electric glare as if they were comfortable showed no difference in the correlation of the daylight discomfort glare metric with the subjective assessments compared to excluding them from the dataset. Nevertheless, the scenes in which discomfort is reported as being caused by the computer screen or the electric lighting were filtered out in order to avoid having to modify the subjective assessments made by the subjects on the glare rating scale A. Moreover, daylight discomfort glare metrics could predict veiling or electric glare in some specific conditions that were not encountered in the study in Malaysia [Hirning et al. 2017].

The filtering was done based on the subjective assessment of the visual scene made by the subjects. The subjects had indeed the opportunity to report the cause of their visual discomfort, if they experienced any, in two questions from the subjective assessment part. The first option was to mention it spontaneously in the OEQ. As a reminder, if the subject was not satisfied with the lighting conditions, he/she was asked why through an OEQ:

Which element(s) bother(s) you in the current lighting conditions?

The answers to this OEQ were categorized according to two variables: "What" (What is bothering in the current lighting condi-

tions?) and "Why" (Why is it bothering in the current lighting conditions?).

A following question required the subject to rate discomfort due to glare on the 4-point glare rating scale A going from No, no discomfort to Yes, a large discomfort. If the subject was perceiving discomfort, he/she was asked to report the source of it through a multiple-choice question:

What is the source of your discomfort?
(Multiple replies possible)

- ☐ The window
- ☐ The wall
- ☐ The computer screen
- ☐ The artificial lighting
- ☐ Other: _____

This multiple-choice question was the second option for the subject to report the cause of visual discomfort.

Although the scenes with visual discomfort due to veiling glare or due to discomfort glare from electric lighting were expected to be reported in the two questions, this was not always the case. Therefore, two sets of rules were derived to filter out inappropriate discomfort glare evaluations, which would have to be applied according to what type of subjective assessment would be used in the analyses.

More specifically, if the subjective assessment made on the 4-point scale A is analyzed, then the cleansing rule based on the 4-point scale A and on the answers to the multiple-choice question is applied.

Rule 8 *The discomfort glare evaluation has to be filtered out if:*

- *the rating on the 4-point scale A reports discomfort due to glare, and*

- *the answer to the multiple-choice question reports that the discomfort does not come from daylight (neither from* The window*, nor from* The wall *or* Other *daylight sources), and*
- *the answer to the multiple-choice question reports that the discomfort comes from* The computer screen *or* The artificial lighting*.*

By applying this rule, 62 of the 802 discomfort glare evaluations (around 8%) had to be filtered out.

On the contrary, if the subjective assessment from the OEQ is analyzed, then the cleansing rule based on the OEQ, or rather the two categorical variables deriving from it (Subsection 4.2.3), is applied.

Rule 9 *The discomfort glare evaluation has to be filtered out if:*

- *the "What" variable from the OEQ is classified as* Electric lighting*, and the "Why" variable as* Discomfort glare*, or*
- *the "What" variable from the OEQ is classified as* Computer screen*, and the "Why" variable as* Reflections*, or*
- *the "What" variable from the OEQ is classified as* Computer screen*, and the "Why" variable as* Brightness*.*

By applying this rule, 55 of the 802 discomfort glare evaluations (around 7%) had to be filtered out.

4.3.5 Acclimatization to the Socio-Environmental Context

The main research question of this study aims at investigating the influence of the socio-environmental context on discomfort glare perception from daylight. The study was designed in such a way that four groups from four different socio-environmental contexts are compared. But only because a subject was working in one of the four selected countries at the time of the study does not mean he/she can be associated to that specific socio-environmental context. As explained in Subsection 2.2.3, it was assumed in this study that it takes at least two years of living in a specific context

for a person to become acclimatized to that socio-environmental context.

To be consistent with this acclimatization theory, only the discomfort glare evaluations done by subjects living in the country for at least two years could be used for the study of the socio-environmental context factor. The time that a subject had spent living in the studied socio-environmental context, as well as her/his former living locations, were collected through the questionnaire. A last rule to filter out data was established based on that information, even though this rule would only be applied for the statistical analyses aiming to tackle the main research question of the study, namely the study of the socio-environmental context influence, and not for the analyses investigating the additional research questions related to the other factors and the experimental biases.

Rule 10 *The discomfort glare evaluation has to be filtered out if the subject has not been living in the country where the study is taking place during the last 2 years.*

By applying this rule, 76 of the 802 discomfort glare evaluations (around 9%) had to be removed for the analyses relative to the socio-environmental context.

4.4 Data Summary

The previous Sections 4.1, 4.2, and 4.3 have described how and what data was collected during the study, how the data was processed to derive useful information for the analyses, and at last what cleansing rules were applied to ensure data quality. This section summarizes the data available for the analyses.

The final dataset consists in a series of discomfort glare evaluations for each of which the following variables are known:

- the subjective assessment of discomfort glare:

  More specifically, the subjective assessment of discomfort glare was collected through at least three different questions, and is therefore available in three (Chilean and Belgian studies) or four (Japanese and Swiss studies) different formats:

  1. a binary variable expressing the report or not of discomfort glare from daylight, which was extracted from the categorization of the OEQ answers
  2. a discomfort glare rating on the 4-point glare rating scale A (No, no discomfort - Yes, a small discomfort - Yes, a moderate discomfort - Yes, a large discomfort)
  3. a discomfort glare rating on the 5-point glare rating scale B (Imperceptible - Perceptible - Acceptable - Uncomfortable - Intolerable)
  4. only for the Japanese and Swiss groups, a discomfort glare rating on the 4-point glare rating scale C (Imperceptible - Noticeable - Disturbing - Intolerable)

  Although the original plan was to base the analyses on the discomfort glare ratings made on the 4-point glare rating scale A (Subsection 4.1.5), the binary variable from the OEQ will also be used in the analyses.

- the measurement of discomfort glare:

  The measurement of discomfort glare is available in the form of eight daylight discomfort glare metrics, of which seven (CGI, DGI, DGI_{mod}, DGP, PGSV, $PGSV_{sat}$, L_{mean}) were calculated

based on the luminance maps through the evalglare algorithm, and one (E_v) was measured directly in situ.

- the socio-environmental context of the subject:
  The study was conducted in four countries (Chile, Belgium, Japan, and Switzerland), and the length of time for which the subject had been living in the country was collected in the questionnaire. Therefore, the socio-environmental context (CL, BE, JP, or CH) of each subject was known. The influence of the socio-environmental context on discomfort glare perception will be investigated in Chapter 6.
- several additional factors related to the subject:
  As mentioned in Section 3.2, this study also aims at investigating the influence of additional factors on discomfort glare perception. Therefore, additional factors related to the subject were collected. These factors include:
  - vision-related characteristics, such as the iris pigmentation
  - demographic and general information, such as the age
  - information about present state when taking part in the study, such as the fatigue

  These factors will be investigated in Chapter 7.
- several factors related to the environment and conditions in which discomfort glare was evaluated:
  In addition to the factors related to the subject, additional factors related to the environment and conditions in which discomfort glare was evaluated were also recorded to be investigated in Chapter 7. These additional factors are:
  - the attractiveness of the view through the window
  - the thermal comfort
  - the time of the day
- three variables summarizing the lighting conditions during the study:
  For each discomfort glare evaluation, the type of lighting, the shading device position and the previous modification of the lighting conditions were available as background information on the study conditions.

Depending on the analyses, the cleansing rules previously defined were applied to generate four datasets containing a series of discomfort glare evaluations with all the above information. But each dataset had different discomfort glare evaluations filtered out, and therefore not the same number of data points.

The four datasets were derived for analyses that are:

- using either the discomfort glare rating made on the 4-point glare scale A or the binary glare report from the OEQ as the subjective assessment of discomfort glare from daylight
- aiming to study the influence of either the socio-environmental context of the subject or other potentially influencing factors and experimental biases.

Tables 4.5 to 4.8 summarize the datasets that were used in the four different cases. It should be noted that in these tables, the cleansing rules overlap for several data points.

Data cleansing step	All	Chilean group	Belgian group	Japanese group	Swiss group
Initial Dataset (0)	401 (100%)	85	86	119	111
Stability of Lighting Conditions (1 & 2)	-46 (−11%)	-3 (−4%)	-23 (−27%)	-14 (−12%)	-6 (−5%)
Accuracy of Measures (3 & 4)	-14 (−3%)	-4 (−5%)	-3 (−3%)	-4 (−3%)	-3 (−3%)
Comparability of Visual Scenes (5, 6, 7, 8, & 9)	-97 (−24%)	-28 (−33%)	-22 (−26%)	-35 (−29%)	-12 (−11%)
Acclimatization to the Socio-Env. Context (10)	-38 (−9%)	-0 (−0%)	-5 (−6%)	-1 (−1%)	-32 (−29%)
Final Dataset	234 (58%)	51 (60%)	48 (56%)	70 (59%)	65 (59%)

Table 4.5: Cleansed datasets for the study of the influence of the socio-environmental context based on the subjective assessment made on the 4-point scale A

Data cleansing step	All	Chilean group	Belgian group	Japanese group	Swiss group
Initial Dataset (0)	401 (100%)	85	86	119	111
Stability of Lighting Conditions (1 & 2)	-46 (−11%)	-3 (−4%)	-23 (−27%)	-14 (−12%)	-6 (−5%)
Accuracy of Measures (3 & 4)	-14 (−3%)	-4 (−5%)	-3 (−3%)	-4 (−3%)	-3 (−3%)
Comparability of Visual Scenes (5, 6, 7, 8, & 9)	-100 (−25%)	-28 (−33%)	-23 (−27%)	-36 (−30%)	-13 (−12%)
Acclimatization to the Socio-Env. Context (10)	-38 (−9%)	-0 (−0%)	-5 (−6%)	-1 (−1%)	-32 (−29%)
Final Dataset	232 (58%)	52 (61%)	46 (53%)	69 (58%)	65 (59%)

Table 4.6: Cleansed datasets for the study of the influence of the socio-environmental context based on the binary glare report from the OEQ

Data cleansing step	All
Initial Dataset (0)	401 (100%)
Stability of Lighting Conditions (1 & 2)	-46 (−11%)
Accuracy of Measures (3 & 4)	-14 (−3%)
Comparability of Visual Scenes (5, 6, 7, 8, & 9)	-97 (−24%)
Final Dataset	265 (66%)

Table 4.7: Cleansed datasets for the study of the influence of additional factors based on the subjective assessment made on the 4-point scale A

Data cleansing step	All
Initial Dataset (0)	401 (100%)
Stability of Lighting Conditions (1 & 2)	-46 (−11%)
Accuracy of Measures (3 & 4)	-14 (−3%)
Comparability of Visual Scenes (5, 6, 7, 8, & 9)	-100 (−25%)
Final Dataset	263 (66%)

Table 4.8: Cleansed datasets for the study of the influence of additional factors based on the binary glare report from the OEQ

4.5 Statistical Methods

This section includes amended parts of the study article [Pierson et al. 2018a].

In the previous Sections (4.1, 4.2, 4.3, and 4.4), the methodology to collect, process, and cleanse the data have been described, and a summary of the data available for analyses was given. In this section, the main statistical methods that were used to analyze the collected data are explained from a theoretical point of view. These methods include the Principal Component Analysis (PCA), the Spearman's rank correlation, the Receiver Operating Characteristic (ROC) curve analysis, and the logistic regression analysis. A short Subsection also describes the Bonferroni correction for multiple comparisons.

4.5.1 Bonferroni Correction

The Bonferroni correction is a correction of statistical significance values. This correction should be applied in the case of multiple testing, namely when multiple statistical tests of a hypothesis are performed.

By applying an individual significance method while doing multiple testing, the probability of observing significant results ($p < \alpha$) by chance alone increases linearly [Rice 1989; Cabin et al. 2000], at least when the tested variables are independent of each other. In case of multiple testing, a correction of the significance level (α) is therefore required to reduce the risk of type I error, i.e., of getting a significant result only due to chance.

The Bonferroni correction can be applied without any distributional assumptions. It consists of dividing the significance level by the number of multiple tests [Field et al. 2012; Wasserman 2003]. Therefore, when conducting K statistical tests of the same hypothesis, a level of α/K should be used as a criterion for significance.

4.5.2 Principal Component Analysis

The PCA is a statistical procedure that aims at reducing the dimensionality of a multivariate data set, while retaining as much of the information in the data as possible [Abdi et al. 2010; Everitt 2011]. The PCA is intended for datasets containing quantitative variables (i.e., continuous variables) only, although other similar analyses exist for datasets made of qualitative variables (i.e., ordinal or categorical variables) (e.g., Multiple Correspondence Analysis (MCA) [Le Roux et al. 2010]) or mixed variables (e.g., Factor Analysis For Mixed Data (FAMD) [Pagès 2004]).

In a PCA, the original variables are converted through an orthogonal transformation into a set of new uncorrelated variables called principal components. The principal components are linear combinations of the original variables, defined in such a way that they account for decreasing proportions of the variation associated with the original variables [Abdi et al. 2010; Everitt 2011]. Because a PCA looks at the total variance in a data set, the original variables should have similar scales of measurement so that their variance is comparable and the same weight is given to each original variable. If the original variables have different orders of magnitude, these should be normalized or the PCA should be based on the correlation matrix since correlations values are normalized.

A PCA analysis delivers a list of k principal components, each having their own eigenvalue that can be translated to the percentage of explained variance. The first principal component will therefore have the highest eigenvalue. A scree plot (Figure 4.27) can be drawn from these eigenvalues to visualize the importance of each principal component in explaining the total variance of the data set. In the case of this example (Figure 4.27), the first two principal components can explain around 60% of the variance in the data set.

Moreover, loadings, namely correlations between the original variables and the principal components, are also supplied by a PCA. The loadings related to the first two principal components can be visually analyzed on the variables factor map (Figure 4.28), where

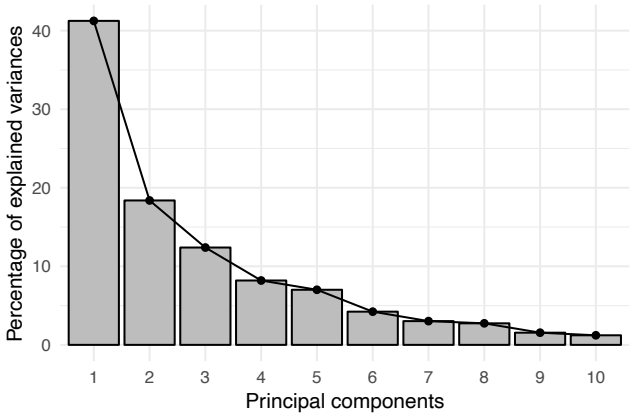


Figure 4.27: Example of scree plot of principal components

the variables are plotted using their loadings as coordinates. In the ideal case of the data being perfectly represented by only two principal components, the variables would be positioned on a circle called the circle of correlations [Abdi et al. 2010]. Most of the time, more than two principal components are needed to explain the total variance of the data set, and the variables are located inside the circle of correlations. The variables factor map is also helpful to visualize clusters of correlated variables. In this example (Figure 4.28), the variables factor map shows that Variable 3 and Variable 7 are highly correlated.

In this research, the PCA is only used to reduce the number of discomfort glare metrics while keeping most of the information given by these metrics.

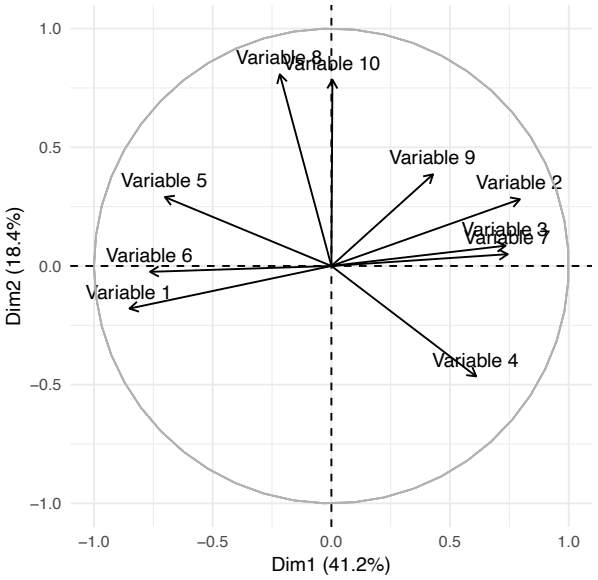


Figure 4.28: Example of variables factor map

4.5.3 Spearman's Rank Correlation

A correlation coefficient is a dimensionless statistic representing how closely two variables are linearly associated. Its value varies from -1 (perfect negative linear relationship) through 0 (no relationship) to +1 (perfect positive linear relationship) [Mukaka 2012]. There exist several correlation coefficients, of which the usage depends on the types of variables being studied. In the case of a correlation including an ordinal variable, which is the case for the following analyses, Spearman's rank correlation has to be used [Mukaka 2012].

The Spearman's rank correlation is a non-parametric technique for evaluating the correlation between two variables using the rank of the data instead of their raw value [Siegel 1956; Gauthier 2001]. Benchmarks have been defined (Table 4.9) to categorize the effect size of a correlation coefficient ρ.

Although the practice of using effect size benchmarks to interpret

[Ferguson 2009]	
$\rho > 0.2$	Practically significant effect
$\rho > 0.5$	Moderate effect
$\rho > 0.8$	Strong effect
[Cohen 1992]	
$\rho > 0.1$	Small effect
$\rho > 0.3$	Medium effect
$\rho > 0.5$	Large effect

Table 4.9: Effect size benchmarks for correlation coefficients

results has been criticized [Ellis 2010], both series shown in Table 4.9, and especially that of Cohen [Bosco et al. 2015], are largely applied in the literature. What matters when interpreting results is that the interpretation should be context-specific [Ferguson 2009] and the effect size benchmarks should be defined according to that context [Cohen 1988].

In a recent study on discomfort glare from daylight [Wienold et al. 2019], it was observed that the interpretation of the results of Spearman's rank correlations according to Cohen's benchmarks was more in accordance with the interpretation of the results of another test, the ROC curve analysis (Subsection 4.5.4). Cohen's effect size benchmarks were therefore applied in that study.

In another study on discomfort glare from daylight [Kent 2016], the results were compared to Ferguson's effect size benchmarks since these were more conservative. The same rationale was applied in a recent study on perceptual effects of daylight patterns [Chamilothori 2019], as it was argued that Cohen's benchmarks were too low, and thus too generous as effect size benchmarks.

Since there is no universal agreement in the field of discomfort glare research on which effect size benchmarks to use, the results of Spearman's rank correlation will be compared to the benchmarks proposed by Ferguson. The main reasons for this choice are to favor the most conservative method, and to avoid drawing incorrect conclusions due to Cohen's low benchmark of practical significance

and the noise inherent to field study data.

4.5.4 Receiver Operating Characteristic Curve Analysis

Prediction models in discomfort glare can be used for two main goals: to determine the severity of discomfort glare that is perceived (i.e., a regression model), or to discriminate between whether glare is perceived or not (i.e., a classification model). The ROC curve analysis is applied to models aiming for the second goal, thus models proposing a binary classifier system, to evaluate their diagnostic ability.

In general, prediction models produce an outcome on a continuous scale. A cut-off value can be defined on this scale to act as the binary classifier system. The outcome values located below this cut-off value are then classified as a null outcome, and those above as a positive outcome. For each cut-off value of the scale, a confusion matrix can be drawn using a dataset with a binary dependent variable (Table 4.10). The True Positive Rate (TPR), or sensitivity, and True Negative Rate (TNR), or specificity, corresponding to each cut-off value can be determined from that confusion matrix. In the case of a discomfort glare prediction model, i.e. a discomfort glare metric, the TPR associated to a defined cut-off value could correspond to the prediction rate of discomforting glare, and the TNR to the prediction rate of no or non-discomforting glare.

		Predicted Values		
		Positive	Negative	
Real Values	Positive	True Positive	False Negative	$TPR = \frac{TP}{(TP+FN)}$
	Negative	False Positive	True Negative	$TNR = \frac{TN}{(FP+TN)}$

Table 4.10: Confusion matrix to evaluate the TPR and TNR

The ROC curve of a prediction model (Figure 4.29) is a plot of the TPR and TNR of a range of cut-off values [Cook 2007]. The ROC curve, of which each point corresponds therefore to a different cut-off value, illustrates the ability of the model to discriminate between two outcomes [Wienold et al. 2019].

The most common method to analyze the ROC curve of a prediction

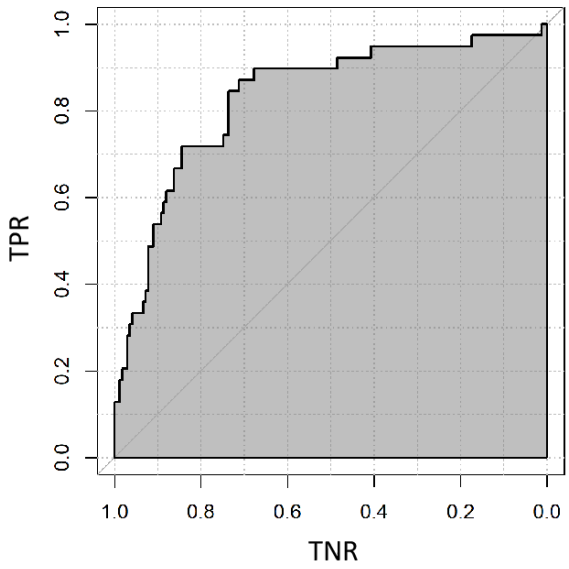


Figure 4.29: Example of a ROC curve

model is to evaluate the Area Under the Curve (AUC), namely the grayed zone in Figure 4.29. The AUC describes the general ability of a model to discriminate between two outcomes, with a value of 0.5 standing for a random discrimination, and a maximum value of 1 for a perfect discrimination [Cook 2007]. The larger the AUC, the better the model, as the TPR and TNR are maximized. AUC benchmarks have been used in the literature to categorize a prediction model according to its diagnostic ability [Hosmer et al. 2013; Safari et al. 2016]:

- AUC$<$ 0.6: failing model
- 0.6 $\leq$AUC$<$ 0.7: poor model
- 0.7 $\leq$AUC$<$ 0.8: acceptable model
- AUC$\geq$ 0.8: excellent model

Considering a discomfort glare metric as the prediction model, the AUC would represent the ability of that metric to discriminate between discomforting and no or non-discomforting glare.

4.5.5 Logistic Regression Analysis

To describe the relationship between a dependent (or outcome) variable and one or more independent (or explanatory) variables, the most common method is the regression analysis. While linear regression models are applicable to continuous dependent variables, logistic regression models are applicable to binary or dichotomous variables. A binary variable can take two values, usually labeled as 0 for no event and 1 for an event. The difference in the type of dependent variable impacts both the model and the assumptions of the regression [Hosmer et al. 2013].

The prediction of a logistic regression model is the probability of a positive event of the binary variable, thus in the range $[0, 1]$. To understand the basis of the logistic regression model [Everitt 2011], it is hypothesized that this prediction (p) can be modeled by a linear function of the independent variables (Equation 4.10).

$$p = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k \tag{4.10}$$

However, the linear function can yield infinite values whereas the probability of a positive event is limited to the range $[0, 1]$. A logit transformation (Equation 4.11 and Figure 4.30) is applied to this prediction (Equation 4.12) since the logit function of a probability can take values outside the range $[0, 1]$.

$$f(x) = \log\left(\frac{x}{1-x}\right) \tag{4.11}$$

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k \tag{4.12}$$

From Equation 4.12, the logistic regression model can be rewritten in such a way that the odds ratios e^{β_i} are better interpretable (Equation 4.13). Moreover, thanks to the logit transformation, the outcome of Equation 4.13, namely the probability of the event, is included in the range $[0, 1]$.

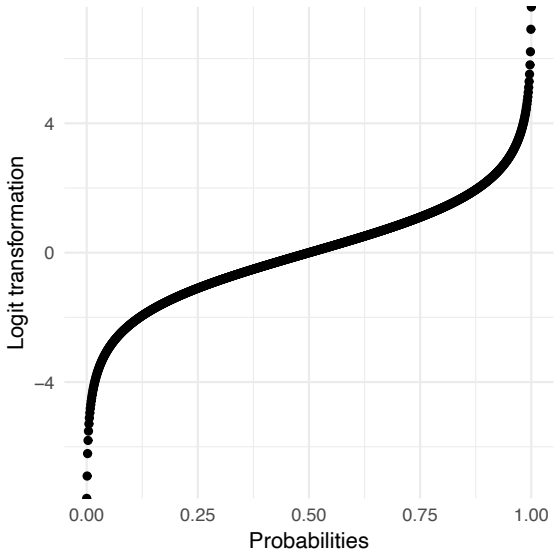


Figure 4.30: Logit transformation

$$p = \frac{e^{\beta_0+\beta_1 x_1+\cdots+\beta_k x_k}}{1+e^{\beta_0+\beta_1 x_1+\cdots+\beta_k x_k}} \tag{4.13}$$

Fitting a logistic regression model to a data set consists therefore in estimating the parameters β_i corresponding to each independent variable in order to best express the probability of an observed outcome. The parameters, as well as the intercepts, of logistic regression models are found via Maximum-Likelihood Estimation (MLE). The MLE yields values for these parameters in order to maximize the probability of obtaining the observed set of data [Hosmer et al. 2013].

The most basic logistic regression model uses a unique independent variable to describe a binary dependent variable, and can be graphically represented by a logistic growth curve having an S-shape (Figure 4.31).

Other types of logistic regression models exist, such as the multiple logistic regression model when there is more than one independent variable, the multinomial logistic regression model when the depen-

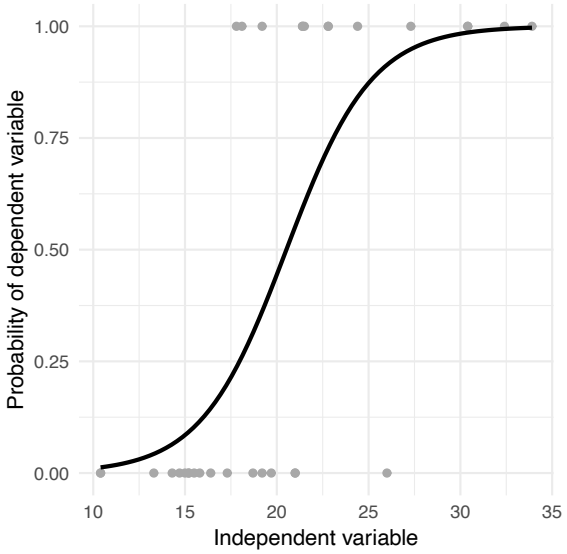


Figure 4.31: Example of a logistic growth curve

dent variable can take more than two values, or the ordinal logistic regression model when the dependent variable can take more than two ordered values.

For this research, the multiple logistic regression model is used to understand the functional relationship between the independent variables and the dependent variable, and to try to determine which independent variables influence this dependent variable [McDonald 2014].

Moreover, there exist several tests to assess whether an independent variable influences in a statistically significant way the dependent variable. Two different statistical tests are applied in this research, namely the Wald test and the Likelihood Ratio Test (LRT).

The Wald test is the default test used in software (such as R) to produce a p-value for the statistical significance of each independent variable when performing a logistic regression.

As mentioned previously, a parameter is first assigned to each independent variable of a logistic regression model via the MLE.

For continuous variables, the parameters can be evaluated directly. However, categorical independent variables first need to be divided into several binary independent variables, with one of the categories used as the control group (Figure 4.32). Each binary independent variable is then assigned a parameter via the MLE.

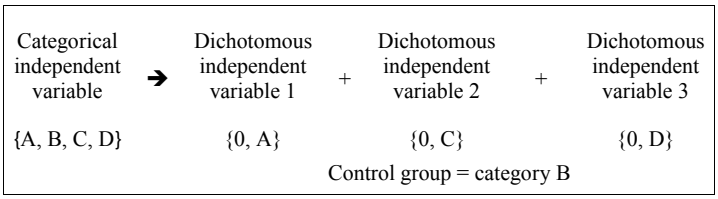


Figure 4.32: Transformation of a categorical variable into binary variables

The null hypothesis of the Wald test determines that the parameter of an independent variable in the logistic regression model equals zero. In other words, the null hypothesis establishes that there is no relationship between the independent variable and the dependent variable [McDonald 2014]. For a univariate model for instance, the Wald statistic is evaluated according to Equation 4.14 [Wasserman 2003].

$$W = \frac{\hat{\theta} - \theta_0}{\hat{se}} \tag{4.14}$$

where:

W is the Wald test statistic

$\hat{\theta}$ is the maximum likelihood estimate of the parameter of interest θ

θ_0 is a scalar parameter, usually equal to 0

$\hat{se}$ is the estimated standard error of the maximum likelihood estimate

The associated p-value can be obtained since the test statistic follows a normal distribution. If the p-value of the test is lower than

the significance threshold, the null hypothesis is rejected. The independent variable is therefore assumed to have a statistically significant influence, as its parameter should be different than 0 in the model, inducing a change in the dependent variable.

The LRT is used in this research to test whether the categorical independent variable influences the binary dependent variable, without having to divide this categorical variable into several binary ones. For the test, two logistic regression models are generated: one in which the categorical independent variable is used as an independent variable; and one without this categorical independent variable. The LRT is performed by comparing the fit of one model to the fit of the other, which means evaluating the difference between the log-likelihoods of the two models (Equation 4.15).

$$\delta = -2 \cdot (\log \max[L(M_2 \mid Data)] - \log \max[L(M_1 \mid Data)]) \quad (4.15)$$

where:

δ is the log-likelihood ratio test statistic

$L_k(M \mid Data)$ is the likelihood score of the model M given the data

M_2 is the multiple logistic regression including the categorical independent variable

M_1 is the multiple logistic regression not including the categorical independent variable

The associated p-value can be obtained, given the known number of degrees of freedom, since the test statistic follows a χ^2 distribution [Pevsner 2015]. If this p-value is lower than the significance threshold, the difference of fit between the two models is statistically significant. The categorical independent variable is then assumed to be a statistically significant variable in predicting the dependent variable [Hosmer et al. 2013].

Chapter 5

Descriptive and Preparatory Analyses

5.1 Introduction

In the previous chapter, the methodology applied to study the influence of the socio-environmental context on discomfort glare perception from daylight is described.

A cross-sectional field study was conducted in office buildings in Chile, Belgium, Japan, and Switzerland, and discomfort glare evaluations were collected at the office desk of each subject, together with 13 additional factors. In total, 802 discomfort glare evaluations of 401 subjects were collected. The raw data collected was processed and cleansed according to specific rules to ensure data relevance and quality. For the analyses of the socio-environmental context influence based on the subjective assessment made via the 4-point glare rating scale A, the final dataset contains 234 discomfort glare evaluations (Table 4.5), whereas for the analyses based on the subjective assessment made via the OEQ, the dataset contains 232 evaluations (Table 4.6).

In this chapter, the processed and cleansed raw data are described in terms of lighting conditions and subjects' demographic characteristics for each socio-environmental context. The aim is to have a better overview of the collected data in each context. It should be noted that the lighting conditions of the offices described in this chapter are most probably not representative of the offices in general in each context. This is due to the fact that the number of office buildings visited per context is low, especially in Chile and Switzerland, and only specific office stations were selected for the study (Section 4.1.4).

Furthermore, additional preparatory analyses are conducted to devise the final subset of discomfort glare metrics. The reason for creating a subset from the already preselected metrics and the way of doing it are described at the end of this chapter.

The descriptive statistical analyses and the subset selection method are applied on a combination of the datasets presented in Tables 4.5 and 4.6. More specifically, since the subjective assessments are not used in the analyses of this chapter, the eighth and ninth data

cleansing rules, which control for scenes reported as discomforting due to veiling glare or due to discomfort glare from electric lighting, are applied together. Hence, only the data points for which the subjective assessments refer to veiling glare or discomfort glare from electric lighting in both methods (glare rating scale A and binary glare report from OEQ), are excluded from the dataset. The merged datasets are displayed in Table 5.1.

Dataset	Glare evaluation	
	First	Second
CL	61	54
BE	56	51
JP	78	72
CH	68	66

Table 5.1: Information on the datasets used for the descriptive analyses of the lighting conditions and subjects demographics in each socio-environmental context (Sections 5.2 and 5.3)

5.2 Description of the Lighting Conditions

5.2.1 Original Lighting Conditions

Firstly, the lighting conditions of the first glare evaluation, namely the original lighting conditions in which the subject was working before the field study started, are described. These conditions are expected to be comfortable, since people usually do not work in uncomfortable conditions, and to meet the lighting requirements that have been defined in each socio-environmental context.

Descriptive statistics (minimum, maximum, mean, median, and standard deviation) of the vertical and horizontal illuminances experienced by the subject in each context in the original lighting conditions are displayed respectively in Tables 5.2 and 5.3.

Socio-environmental context	Vertical illuminance [lux]				
	Min.	Max.	Mean	Median	SD
CL	109	1601	511	390	375
BE	98	2520	618	455	522
JP	136	3090	641	491	531
CH	100	2500	586	468	454

Table 5.2: Descriptive statistics (minimum, maximum, mean, median, and standard deviation) of the vertical illuminance in the original lighting conditions for the four socio-environmental groups

Socio-environmental context	Horizontal illuminance [lux]				
	Min.	Max.	Mean	Median	SD
CL	NA	NA	NA	NA	NA
BE	109	1801	691	556	398
JP	104	2949	873	770	506
CH	53	2604	557	501	397

Table 5.3: Descriptive statistics (minimum, maximum, mean, median, and standard deviation) of the horizontal illuminance in the original lighting conditions for the four socio-environmental groups

These descriptive statistics are also graphically displayed in Figure 5.1 (box plots of the vertical illuminance), and in Figure 5.2 (box plots of the horizontal illuminance).

The tables and graphs indicate that the original lighting conditions

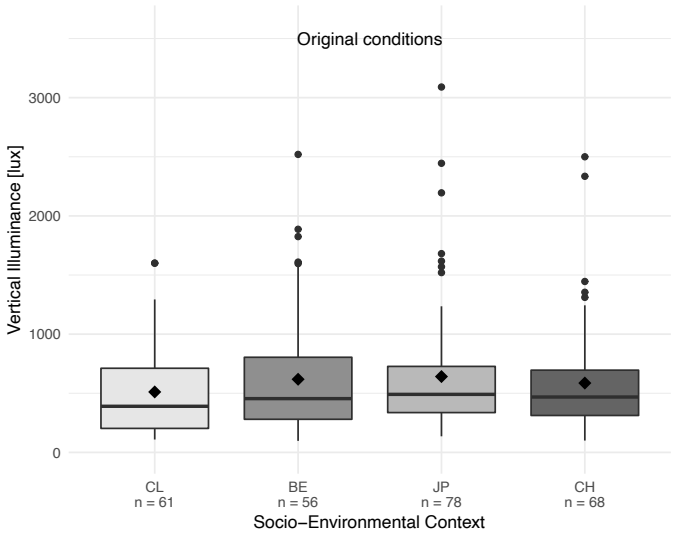


Figure 5.1: Box plots representing the distribution of the data for the vertical illuminance during the original lighting conditions in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

were on average a bit brighter in the Japanese context, and a bit darker in the Chilean context, compared to the European contexts.

As a reminder, the recommended horizontal illuminance on the desk in Japanese offices is 750 lux; the recommended horizontal illuminance on the desk in European offices is 500 lux; and the recommended horizontal illuminance on the desk in Chilean offices is 400 lux.

On average, the recommended horizontal illuminance on the desk is met for the Belgian, Japanese, and Swiss contexts, with median horizontal illuminance values of respectively 556, 770, and 501 lux. However, these values also mean that for around half of the offices studied in these contexts, the recommended horizontal illuminance on the desk is not met. Since the horizontal illuminance on the desk could not be recorded in the Chilean context, the comparison with the recommended value cannot be made.

Furthermore, the luminance ranges in the subjects' FOV in the orig-

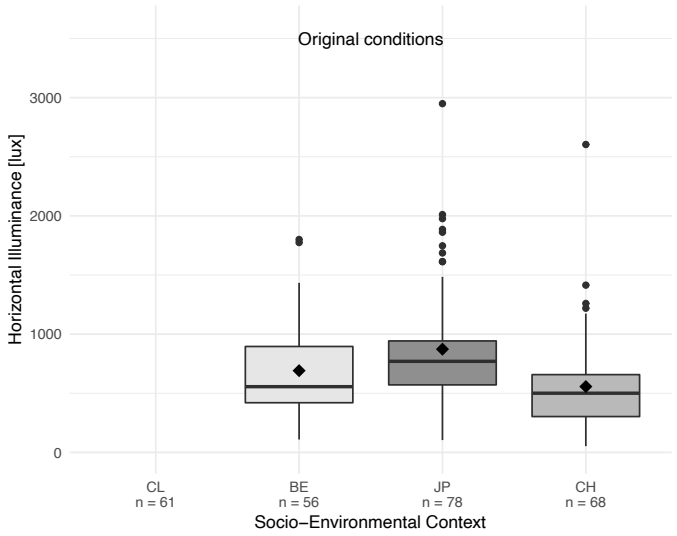
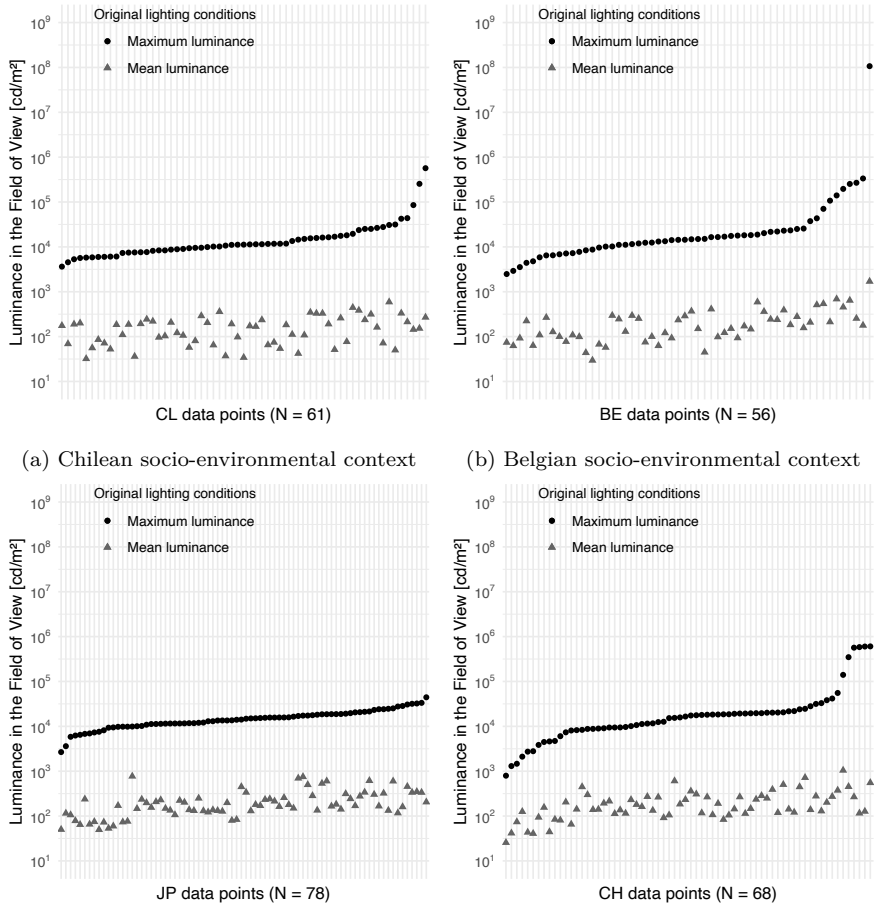


Figure 5.2: Box plots representing the distribution of the data for the horizontal illuminance during the original lighting conditions in three socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

inal lighting conditions can be analyzed for each socio-environmental context. More specifically, the maximum and mean luminance values in the FOV are displayed in Figure 5.3 for each subject in each context.

In Figure 5.3, it can be observed that most of the maximum and mean luminance values in the subjects' FOV were in the same order of magnitude in the four contexts, i.e., 10^4 cd/m^2 for the maximum luminance and 10^2 cd/m^2 for the mean luminance. There are, however, several higher maximum luminance values in the Chilean, Belgian, and Swiss datasets, and several lower maximum luminance values in the Swiss dataset, compared to the Japanese one. In the Japanese dataset, the luminance ranges of the original lighting conditions seem relatively constant throughout all the participants, although this dataset was collected in 13 different buildings (against respectively four, seven, and four buildings in Chile, Belgium, and Switzerland).



(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

Figure 5.3: Scatter plots of the maximum and mean luminance values in the subjects' FOV in the original lighting conditions for the four socio-environmental groups

5.2.2 Maximized Daylight Conditions

Secondly, the lighting conditions of the second glare evaluation, namely the conditions in which daylight was maximized to increase the occurrence of daylight discomfort glare, are described.

Descriptive statistics (minimum, maximum, mean, median, and standard deviation) of the vertical and horizontal illuminances experienced by the subject in the maximized daylight conditions are

displayed respectively in Tables 5.4 and 5.5 for each socio-environmental context.

Socio-environmental context	Vertical illuminance [lux]				
	Min.	Max.	Mean	Median	SD
CL	126	29600	1571	858	3979
BE	85	4060	815	571	841
JP	58	5085	939	711	859
CH	199	18475	2289	1060	3693

Table 5.4: Descriptive statistics (minimum, maximum, mean, median, and standard deviation) of the vertical illuminance in the maximized daylight conditions for the four socio-environmental groups

Socio-environmental context	Horizontal illuminance [lux]				
	Min.	Max.	Mean	Median	SD
CL	NA	NA	NA	NA	NA
BE	72	34749	1903	653	6009
JP	44	3241	847	700	721
CH	208	39774	2891	907	7863

Table 5.5: Descriptive statistics (minimum, maximum, mean, median, and standard deviation) of the horizontal illuminance in the maximized daylight conditions for the four socio-environmental groups

These descriptive statistics are also graphically displayed in Figure 5.4 for the box plots of the vertical illuminance, and in Figure 5.5 for the box plots of the horizontal illuminance.

The tables and graphs show that the maximized daylight conditions were on average a bit brighter in the Swiss context and a bit darker in the Belgian context than in the non-European ones. Moreover, there seem to be extreme vertical illuminance values in both the Chilean and Swiss contexts, as well as extreme horizontal illuminance values in both the Belgian and Swiss contexts, as the mean is much larger than the median for these contexts in Figures 5.4 and 5.5.

The luminance ranges in the subjects' FOV in the maximized daylight conditions can also be analyzed for each socio-environmental context. More specifically, the maximum and mean luminance values in the FOV are displayed for each subject of each context in Figure 5.6.

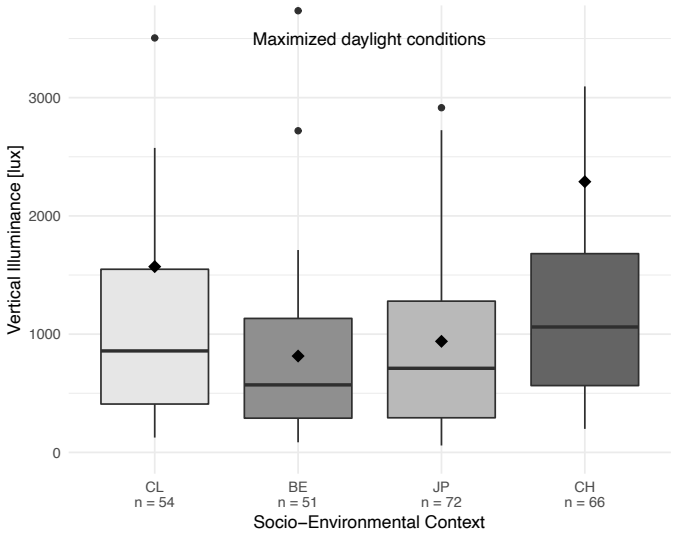


Figure 5.4: Box plots, representing the distribution of the data for the vertical illuminance during the maximized daylight conditions in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

In Figure 5.6, eight outliers (one in the Chilean dataset and seven in the Swiss dataset) can be visually detected. These very high maximum luminance values in the subjects' FOV in these two contexts are indicative of the large differences between the mean and median vertical illuminance in Figure 5.4. The images corresponding to these extreme values were visually inspected, and it appeared that the sun was in the FOV for each of them, as observed in Figure 5.7.

The sun in the FOV was also the main reason for the large differences between the mean and median horizontal illuminance in the Swiss dataset in Figure 5.5. However, one visual scene in the Swiss context and two visual scenes in the Belgian context, of which the horizontal illuminance values are partially responsible for the large differences between the mean and median horizontal illuminance in these contexts, did not have the sun in the FOV. However, the sun most probably was in the FOV of the horizontal illuminance sensor on the desk, as observed in Figure 5.8.

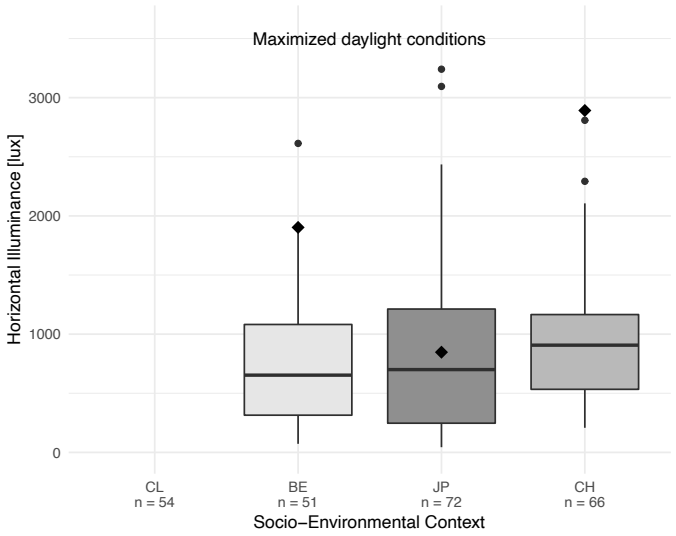
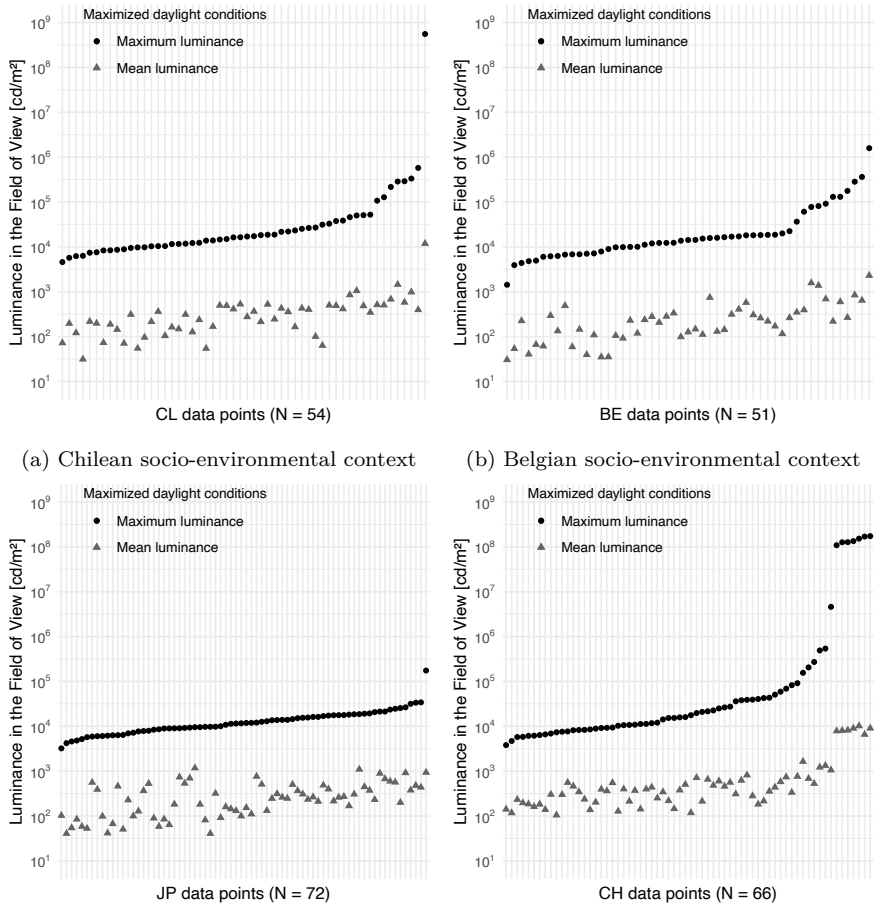


Figure 5.5: Box plots, representing the distribution of the data for the horizontal illuminance during the maximized daylight conditions in three socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers



(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

Figure 5.6: Scatter plots of the maximum and mean luminance values in the subjects' FOV in the maximized daylight conditions for the four socio-environmental groups



Figure 5.7: Visual scene of the Swiss dataset in the maximized daylight conditions with the sun in the subject's FOV



Figure 5.8: Visual scene of the Belgian dataset in the maximized daylight conditions with the sun in the horizontal illuminance sensor's FOV

5.2.3 Main Type of Lighting

At last, based on the relationship between vertical and horizontal illuminance, the main type of lighting can be hypothesized in the offices studied in each context. Indeed, as none of the visual scenes had skylights, it could be expected that if the horizontal illuminance sensor received more light than the vertical one, more light came from the ceiling, hence from electric lighting, than from the window.

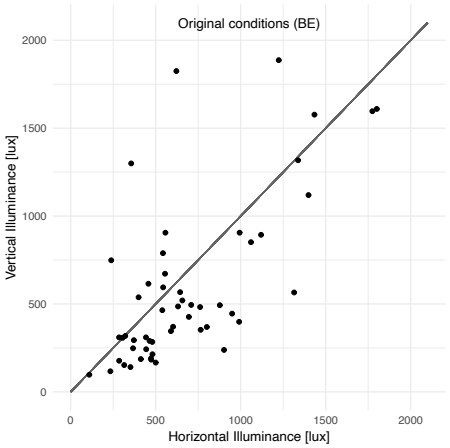
The graphs displaying the vertical illuminance in function of the horizontal illuminance are available in Figure 5.9 for the original lighting conditions, and in Figure 5.10 for the maximized daylight conditions. Since there was no measurement of horizontal illuminance in Chile, the analysis cannot be performed for this context.

In the graphs in Figure 5.9, it can be observed that, in the Japanese context, more light reached the horizontal illuminance sensor than the vertical illuminance sensor. This observation suggests that the surveyed Japanese office workers tend to work mostly in electric lighting conditions. This trend is in line with the investigator's experience while conducting the study in Japan, as a large part of the subjects were working with their shading devices closed. Regarding the Belgian and Swiss socio-environmental contexts, there is no visible trends in the graphs in Figure 5.9, which could suggest that the lighting conditions were balanced between daylight and electric light.

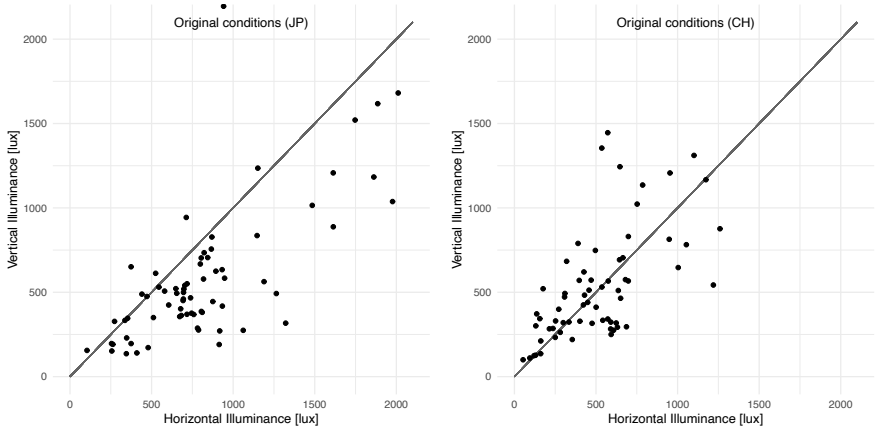
On another note, in Figure 5.10, the tendency towards higher horizontal illuminance levels than vertical illuminance levels in the Japanese context has disappeared, most probably because the shading devices were opened in the maximized daylight conditions. Moreover, in the Swiss socio-environmental context, the vertical illuminance levels seem to be higher than the horizontal ones, which could suggest that these visual scenes were mainly daylit.

This last observation is likely, as the size of the windows were the largest in the Swiss socio-environmental context.

The size of the windows in the subjects' FOV are evaluated by their solid angles. The distributions of the solid angles of the windows for



(a) Belgian socio-environmental context

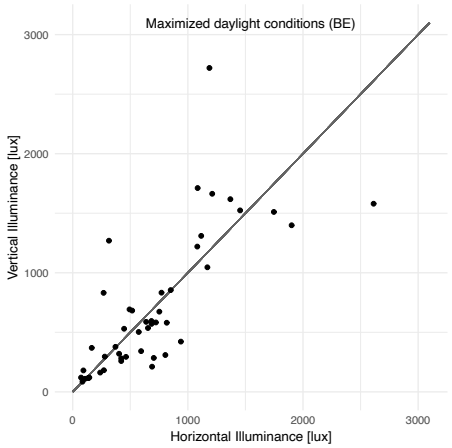


(b) Japanese socio-environmental context (c) Swiss socio-environmental context

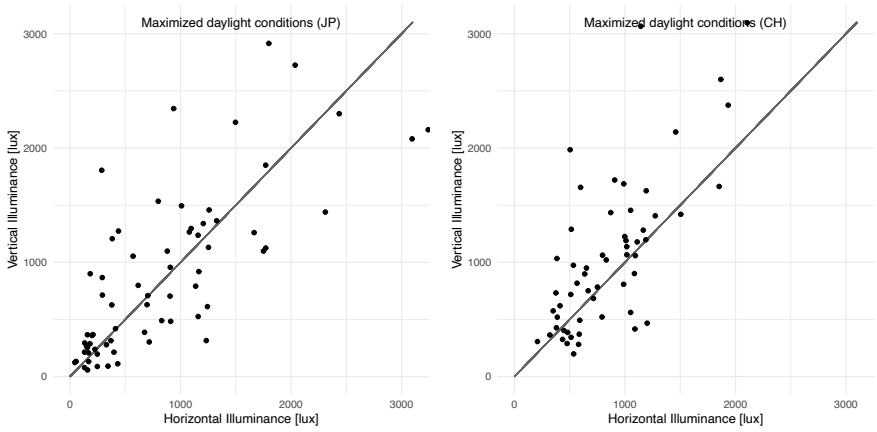
Figure 5.9: Scatter plots of the vertical illuminance in function of horizontal illuminance in the original lighting conditions for three socio-environmental groups

each socio-environmental context are displayed in the box plots in Figure 5.11. The solid angle of the window only includes the portion of the window visible from the seated position of the subject. Hence, any parts of the window hidden from the subject when seated at her/his desk by an object or a piece of furniture, but not by the shading devices, are not included in that solid angle.

Furthermore, a visual inspection of Figure 5.11 indicates that the



(a) Belgian socio-environmental context



(b) Japanese socio-environmental context (c) Swiss socio-environmental context

Figure 5.10: Scatter plots of the vertical illuminance in function of horizontal illuminance in the maximized daylight conditions for three socio-environmental groups

windows occupied a smaller portion of the Japanese subjects' FOV than in the FOV of the subjects from the other contexts.

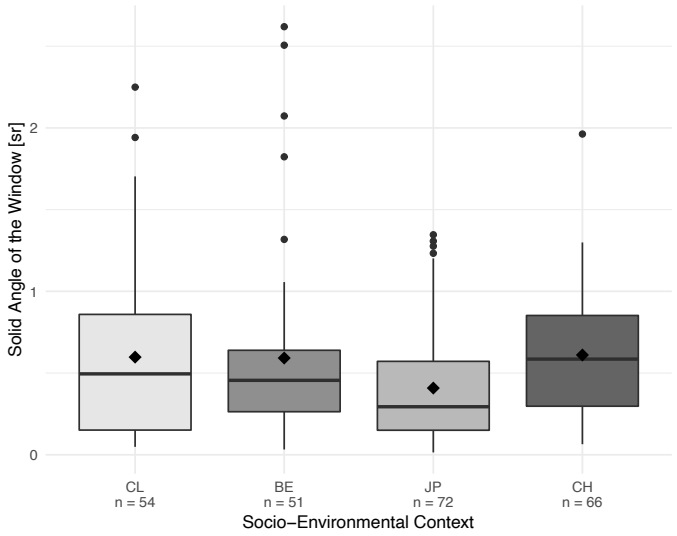


Figure 5.11: Box plots representing the distribution of the data for the solid angle of the window as seen by the subject in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

5.3 Description of the Subjects

Firstly, basic demographic characteristics of the dataset for each socio-environmental context are described in Tables 5.6 and 5.7. These demographic characteristics are the gender and the age of the subjects. The distributions of these characteristics for each socio-environmental context, as well as other baseline characteristics, are graphically displayed in Figure 6.2 in Chapter 6.

Socio-environmental context	Gender		
	Men	Women	Men [%] / Women [%]
CL	28	26	52%/48%
BE	21	30	41%/59%
JP	46	26	64%/36%
CH	39	27	59%/41%

Table 5.6: Descriptive statistics (counts and proportions) of the gender of the subjects in the four socio-environmental groups

Regarding the gender of the subjects, Table 5.6 indicates that the proportions of men and women are relatively similar for each context, except maybe in the Japanese dataset where there is a bit more men.

Socio-environmental context	Age [years]				
	Min.	Max.	Mean	Median	SD
CL	28	67	44	41	9
BE	24	73	39	37	12
JP	21	64	34	29	12
CH	17	61	36	34	11

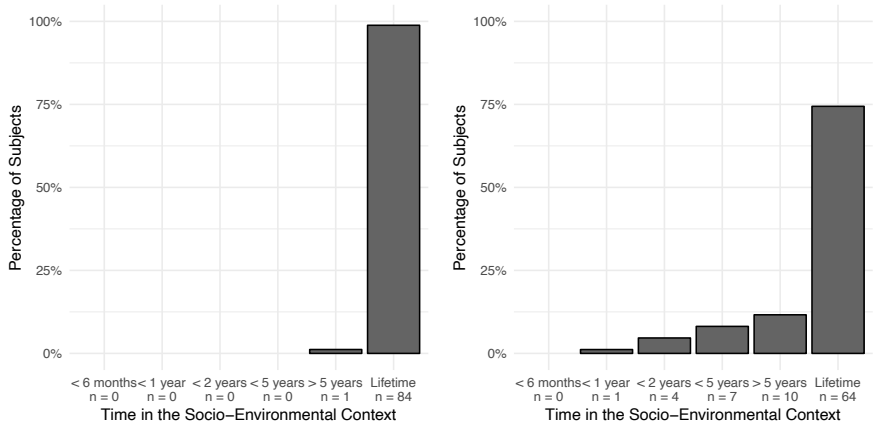
Table 5.7: Descriptive statistics (minimum, maximum, mean, median, and standard deviation) of the age of the subjects in the four socio-environmental groups

Regarding the age of the subjects, the distributions, summarized by the statistics in Table 5.7, are also relatively similar between the contexts, although there seems to be younger subjects in the Japanese dataset.

Secondly, the acclimatization of the subjects to their respective socio-environmental context is analyzed. This analysis consists

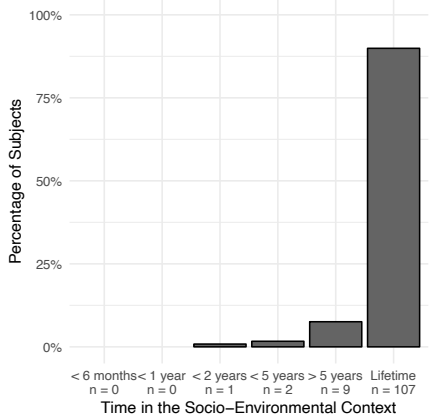
mainly of evaluating for how long the subject has been living in the context, or whether he/she is a native.

If the initially collected data is used, i.e., the data before any data cleansing rules are applied, it can be observed in Figure 5.12 that the Chilean, Japanese, and Belgian datasets are made of a large number of native subjects, in contrast to the Swiss dataset.

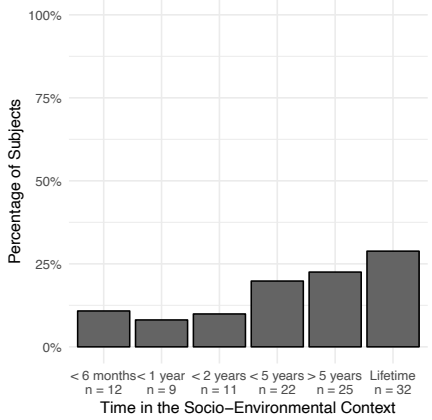


(a) Chilean socio-environmental context

(b) Belgian socio-environmental context



(c) Japanese socio-environmental context



(d) Swiss socio-environmental context

Figure 5.12: Percentage of subjects per category of time lived in the four socio-environmental contexts before the data cleansing rules are applied

Furthermore, the subjects of that dataset, thus the Swiss dataset

before the cleansing rules are applied, come from very diverse countries of origin, as indicated in Figure 5.13.

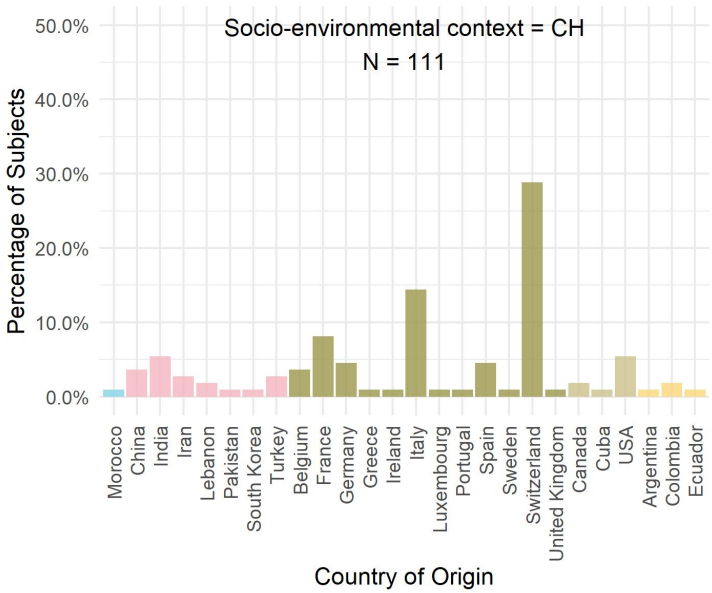
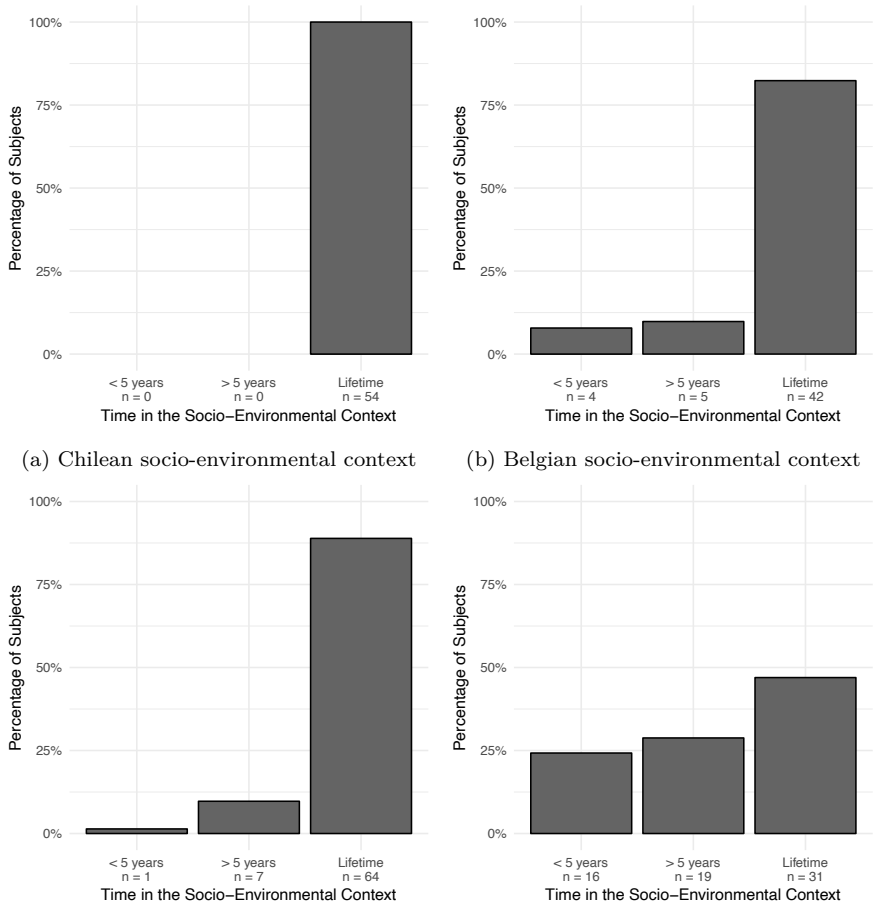


Figure 5.13: Countries of origin of the subjects of the Swiss dataset before the data cleansing rules are applied; the colors of the graph represent the different continents

However, for the analyses related to the influence of the socio-environmental context on discomfort glare perception, a data cleansing rule was applied to remove from each dataset the subjects who were supposed not to be acclimatized to the context. This rule establishes that the subject has to be filtered out if he/she has not been living during the last two years in the context where the study takes place. The rule is explained in Subsection 4.3.5.

Therefore, the cleansed datasets are analyzed in Figure 5.14 regarding the acclimatization of the subjects to their respective context.

It can be observed in Figure 5.14d that there is almost half of the subjects of the cleansed Swiss dataset who are natives of this context. The rest of them has been living in the country for at least two years, which means that they can also be considered as acclimatized to the Swiss context according to the cross-cultural



(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

Figure 5.14: Percentage of subjects per category of time lived in the four socio-environmental contexts after the data cleansing rules are applied

adjustment model (Subsection 2.2.3).

Furthermore, the subjects of the Swiss dataset who are not Swiss natives are, for most of them, natives from a European country, as indicated in Figure 5.15.

Therefore, although the investigation of the difference in sensitivities to discomfort glare from daylight between the two European contexts, i.e., Belgium and Switzerland, might be weakened by the

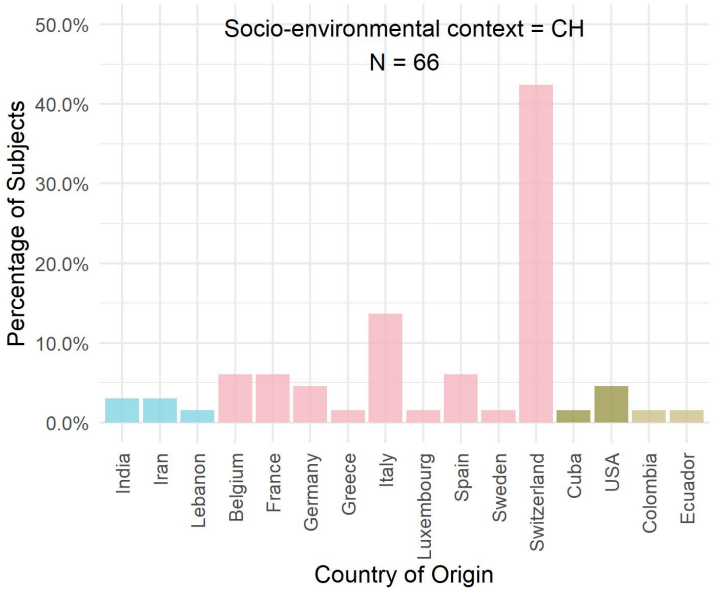


Figure 5.15: Countries of origin of the subjects of the Swiss dataset after the data cleansing rules are applied; the colors of the graph represent the different continents

lack of natives in the Swiss dataset, this should not be an issue for the investigation of the difference between socio-environmental contexts located on different continents, such as with the Chilean and Japanese ones.

5.4 Selection of Discomfort Glare Metrics

At last, before starting the statistical analyses aimed at answering the main research question, a subset of the eight preselected daylight discomfort glare metrics needs to be selected. Selecting a subset of pertinent metrics is required in order for the results of the analyses to be valid for the majority of daylight discomfort glare metrics, without risking to draw erroneous conclusions due to multiple testing.

5.4.1 Multiple Testing

From a first analysis (Subsection 4.2.6), eight metrics have been chosen to be representative of daylight discomfort glare metrics nowadays: the CGI, the DGI, the DGI_{mod}, the E_v, the L_{mean}, the $PGSV_{sat}$, the DGP, and the PGSV.

To comply with Weber-Fechner's law of psychophysics, which establishes that the intensity of a sensation is proportional to the logarithm of the intensity of the stimulus [Fechner 1860], the E_v and L_{mean} metrics should be scaled by applying a logarithmic function. The logarithmic version of E_v and L_{mean} should be used for the following analyses instead of the linear one, since the logarithmic scale better represents human physiological sensations (as for sound).

However, the linear version of these two metrics is much more commonly used in the lighting research field, and offers the advantage to be easily measurable and interpretable. Furthermore, there exists some evidence that subjective assessments of discomfort glare better correlate with the linear version of E_v than with the logarithmic one [Wienold 2009a]. For these reasons, it is decided to keep the linear versions of E_v and L_{mean} in this research. Using the logarithmic versions of these metrics should have little impact on the results, though, since most statistical methods are nonparametric, hence the results are based on the rank values rather than the absolute ones.

If the eight preselected metrics are used for the analyses, each sta-

tistical test needs to be conducted eight times, i.e., once for each metric. As explained in Subsection 4.5.1, multiple statistical tests mean that a Bonferroni correction has to be applied to reduce the risk of type I error.

However, the use of a Bonferroni correction is controversial when the number of multiple tests is high, as it is known to cause a loss of statistical power. In this case, 8 similar statistical tests would be conducted, which would result in a level of 0.00625 to be used as a criterion for significance. This corrected criterion is very strict, and considerably increases the risk of Type II error, i.e., of rejecting an effect that does actually exist [Field et al. 2012; Perneger 1998].

To find a trade-off between an increase in the risks of Type I and Type II errors, a Bonferroni correction is applied, but the number of daylight discomfort glare metrics is reduced to the minimum, so that the correction stays reasonable. A PCA is conducted to detect which metrics behave similarly and should be discarded from the subset that will be used for the analyses.

5.4.2 Principal Component Analysis

As explained in Subsection 4.5.2, a PCA helps subsetting variables that retain as much information in the data as possible. This method is applied to restrict the number of daylight discomfort glare metrics.

For this analysis, the dataset used is the same as for the descriptive statistics considering the maximized daylight conditions (Section 5.1), from which eight outliers are removed, since the PCA is sensitive to outliers. In the descriptive statistics, it was indeed observed that eight E_v values (one in Chile and seven in Switzerland) were very high ($E_v > 6000$ lux) compared to the range of values of the dataset. The final dataset for the PCA is summarized in Table 5.8.

The PCA is performed for the eight preselected metrics using the correlation matrix between these metrics to avoid any issue related to different orders of magnitude between the metrics scales.

The screeplot of the PCA, which shows the first eight principal

Dataset	N
CL	53
BE	51
JP	72
CH	59
Total	235

Table 5.8: Information on the datasets used for the selection of the metrics (Section 5.4) and the analysis of the comparability of the socio-environmental groups (Section 6.2)

components and their respective percentage of explained variance (Figure 5.16), indicates that the first component on its own explains 75% of the variance in the data, and the first two components explain around 88% of the variance.

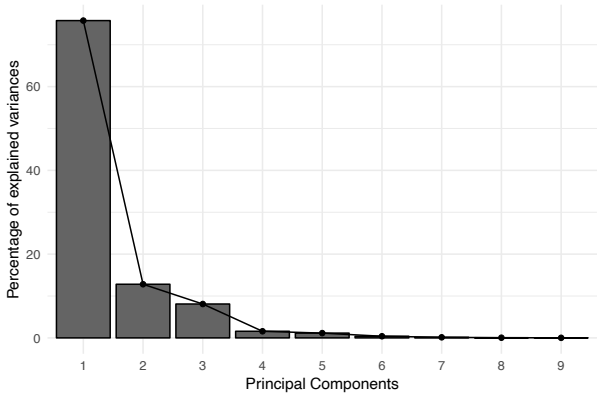


Figure 5.16: Screeplot of the PCA to select a subset from the eight daylight discomfort glare metrics

Moreover, the variables factor map of the PCA shows that all the active variables, namely the eight daylight discomfort glare metrics, are highly correlated with the first principal component (Figure 5.17).

These two observations were expected, since the metrics are supposed to represent the same element, namely discomfort glare, and therefore explain a similar and substantial variance in the data.

Clusters of correlated variables can also be detected in the variables factor map. From Figure 5.17, the clusters representing the

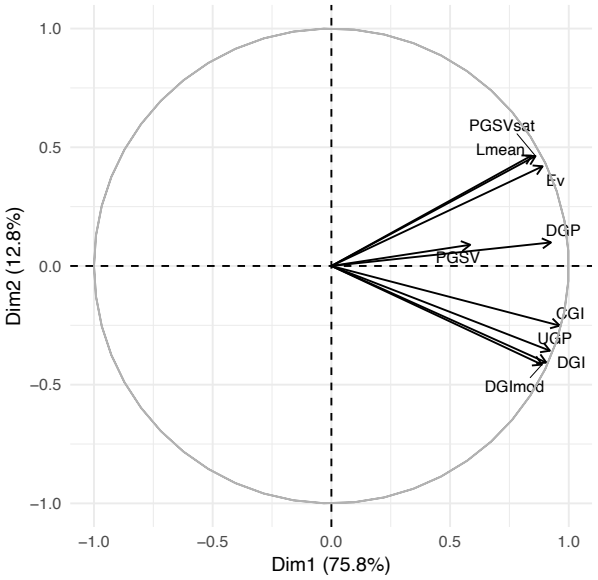


Figure 5.17: Variables factor map of the PCA to select a subset from the eight daylight discomfort glare metrics

three types of discomfort glare metrics can be observed, with the saturation-based metrics above, including the E_v, the L_{mean}, and the $PGSV_{sat}$, the contrast-based metrics below, including the CGI, the DGI, and the DGI_{mod}, and finally, the metrics taking into account both types of glare in the middle, including the DGP, and the PGSV. Interestingly, the second principal component puts slightly in opposition the saturation-based and the contrast-based metrics.

Due to the selection criteria for the visual scenes (Subsection 4.1.4), it was expected that saturation-based metrics would best explain the variance in the data. This is not supported by the PCA results. Indeed, the closer a variable is to the external circle in the factor map (Figure 5.17), the more important it is to interpret the first two principal components [Abdi et al. 2010]. In this case, all the metrics, except for the PGSV, are located close to the circle, implying that each of them is equally important to interpret the two components, and thus 88% of the variance in the data. The

PGSV is therefore removed from the subset of daylight discomfort glare metrics. Moreover, since the DGP becomes the only metric including both types of glare, it is included in the subset.

Finally, to provide a balanced subset of metrics, the same number of saturation-based and contrast-based metrics have to be kept.

The $PGSV_{sat}$ is a function of E_v. Since E_v is more straightforward to calculate and to understand, and since it is the closest to the external circle of the saturation-based metrics, the $PGSV_{sat}$ is discarded. The two least correlated, i.e., further apart in the factor map, and most easily interpreted saturation-based metrics are kept, namely the E_v, and the L_{mean}.

Two contrast-based metrics have to be kept as well. Since the DGI and the DGI_{mod} are almost overlapping in the factor map, and are therefore highly correlated, one of the two is discarded. Being a long-established daylight discomfort glare metric, the DGI is preferred. It is included in the subset besides the CGI.

The final daylight discomfort glare metrics subset includes five metrics, namely the CGI, the DGI, the E_v, the L_{mean}, and the DGP. Each statistical test will therefore be performed for each of these five metrics.

Moreover, a significance level of $\alpha = 0.05$ is assumed for this research, meaning that there is a 5% risk of rejecting the null hypothesis when it is true [Field et al. 2012].By applying the Bonferroni correction, the significance level used in the following analyses is $\alpha = 0.01$ ($\alpha < 0.01^{*}$ for statistical significance; $\alpha < 0.002^{**}$ for statistical high significance; and $\alpha < 0.0002^{***}$ for statistical very high significance).

Chapter 6

Results: Main Research Question

6.1 Introduction

Based on the selected metrics and data described in the previous chapter as well as on the statistical methods explained in Section 4.5, this chapter aims to answer the main research question, which is to determine whether the socio-environmental context of a subject influences her/his discomfort glare perception from daylight.

From the literature (Subsection 2.2.3), it seems that subjects acclimatized to different socio-environmental context have different sensitivities towards discomfort glare from daylight. It is not clear, however, which socio-environmental groups are more sensitive than the others. As the difference in discomfort glare perception between two socio-environmental contexts can have two possible directions, two-tailed tests are used in the statistical analyses. Moreover, the corrected significance level used in the following analyses is $\alpha = 0.01$ ($\alpha < 0.01^{*}$ for statistical significance; $\alpha < 0.002^{**}$ for statistical high significance; and $\alpha < 0.0002^{***}$ for statistical very high significance).

For the results presented in this chapter, the statistical tests are completed with the software R version 3.5.2 [R Core Team 2018], as well as:

- the R package *FactoMineR* version 1.41 [Le et al. 2008] for the PCA;
- the R package *stats* version 3.5.2 [R Core Team 2018] for the Spearman's rank correlations, the χ^2 tests of equal proportions, the fittings of logistic regression models, the Wald tests, the LRT, and the Kruskal-Wallis test;
- the R package *pROC* version 1.13.0 [Robin et al. 2011] for the ROC curve analyses;
- the R package *psych* version 1.8.12 [Revelle 2018] for the Cronbach's α evaluations.

6.2 Comparability of the Socio-Environmental Groups

To investigate the difference in discomfort glare perception between several socio-environmental groups, these groups should be comparable. A fair basis of comparison has to be ensured in terms of baseline characteristics, in order to reduce the risk of extraneous variables confounding the results. In this field study, the baseline characteristics include subject-related variables, such as their gender and age, but also environmental variables, such as the air temperature or the view through the window.

The office layout and the lighting conditions are also baseline characteristics for which a fair basis of comparison has to be provided between the socio-environmental groups compared. These requirements are partly ensured through the application of the selection criteria (Subsection 4.1.4) and some of the data cleansing rules (Subsection 4.3.4). Moreover, since daylight could not be controlled, the distributions of the lighting environment stimuli, i.e., the discomfort glare metric values, in each socio-environmental group should be analyzed to determine whether the lighting conditions were relatively similar. In any case, the daylight discomfort glare metrics will be used as independent variables in most of the analyses, leading to any difference in discomfort glare stimulus between the groups to be taken into account in these analyses.

Since the subjects and their offices were randomly selected between the visual scenes that matched the selection criteria, it is expected that the distributions of most baseline characteristics are relatively similar between the four socio-environmental groups. To guarantee that it is the case, balance tests, also called randomization checks, are recommended. These significance tests, such as the t-test, investigate the null hypothesis that two or more groups have the same mean for one baseline characteristic. In brief, the balance tests are used to indicate whether data randomization has produced balance on baseline characteristics across the groups [Mutz et al. 2011].

However, the use of balance tests has been criticized in the litera-

ture, principally due to the fact that analyzing data on which a balance test has already been conducted could yield anti-conservative p-values and over-conservative results [Mutz et al. 2011; Vanhove 2014; Hayes et al. 2017]. Instead of balance tests, it is recommended to report descriptive statistics of baseline characteristics of the groups, so that the reader can judge how much effect any difference might have on the findings [Hayes et al. 2017]. When a large imbalance is observed for a baseline factor and there are good reasons to think that this factor could have an effect on the results, it is recommended to include this factor in the main analysis [Altman 1985; Vanhove 2014].

To assess the comparability of the socio-environmental groups, the distributions of the baseline characteristics of these groups are shown and analyzed in Subsections 6.2.1 and 6.2.2.

6.2.1 Analyses and Results

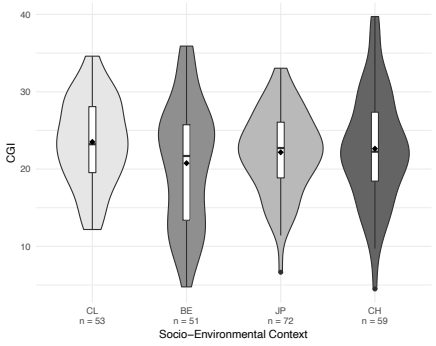
Similarly to Chapter 5, the two datasets (Tables 4.5 and 4.6) derived for the study of the influence of the socio-environmental context on discomfort glare have been merged for the analyses performed in this section. The merged datasets, described in Table 5.8, are used for the assessment of the comparability of the socio-environmental contexts. Eight outliers (one in Chile and seven in Switzerland) have been removed from these datasets due to their high vertical illuminance value ($E_v > 6000$ lux). A visual inspection of the visual scenes of these eight data points show that the sun was present in the FOV of each scene, increasing the risk of disability glare.

First, the balance in discomfort glare stimuli between the four socio-environmental groups is analyzed. For this purpose, the distributions of the five daylight discomfort glare metrics are illustrated in Figure 6.1. The distributions are represented through box plots inscribed inside violin plots. In the box plots, the band inside the box represents the median; the box limits represent the 25th and 75th percentiles; the whiskers represent respectively the smallest value within 1.5 times interquartile range below the 25th percentile, and the largest value within 1.5 times interquartile range above the 75th

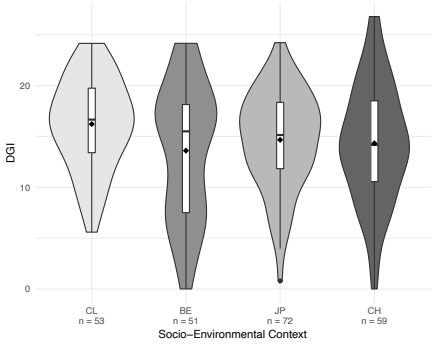
percentile; and the dots represent the outliers. The violin plots are mirrored density plots, as they depict the kernel probability density of the data at different values. Lastly, the mean is also displayed in the graph via a diamond dot.



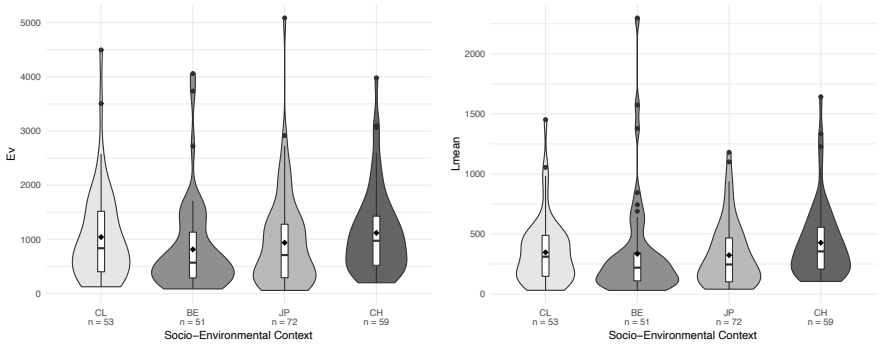
(a) DGP



(b) CGI



(c) DGI



(d) E_v (e) L_{mean}

Figure 6.1: Violin plots, representing the density of the data, and box plots, representing the distribution of the data, for the five daylight discomfort glare metrics in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

A visual inspection of the plots in Figure 6.1 leads to hypothesize that the distributions of the five daylight discomfort glare metrics are relatively similar for the four socio-environmental contexts. Consequently, it is assumed that the distributions of the discomfort glare stimuli, and more generally of the lighting conditions, are balanced when the outliers are removed.

These eight outliers, which lie in the range of 7360 to 29600 lux, were all found in the Swiss dataset except for one in the Chilean dataset. As the sun was present in these eight visual scenes, the outliers were permanently removed from the datasets to prevent them from corrupting the results due to their extreme values. Moreover, it is assumed that these visual scenes fall in the category of disability glare, which is not the focus of this research.

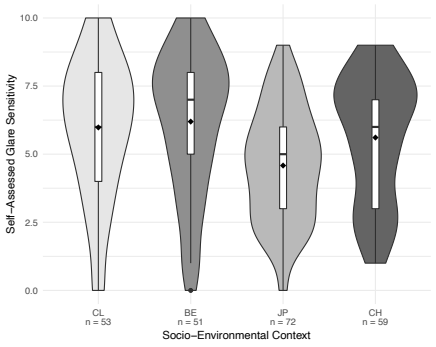
Then, the distributions of the baseline characteristics are inspected for the four socio-environmental groups in Figures 6.2 and 6.3. The baseline characteristics that are investigated are:

1. subject-related factors
    - age
    - self-assessed glare sensitivity
    - gender
    - handedness
    - optical correction
    - iris pigmentation
    - chronotype
    - caffeine ingestion
    - physical state
    - emotional state
    - fatigue
2. Environment-related factors
    - air temperature
    - attractiveness of the view through the window
    - time of day
    - lighting conditions modification

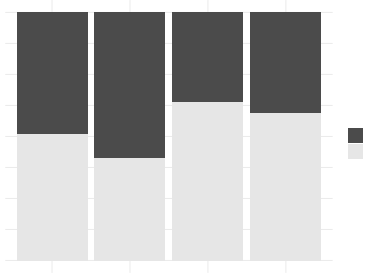
As shown in Section 5.2, the original lighting conditions were different in each office. The lighting conditions modification variable represents the number of offices where the lighting conditions were modified, either by turning off the electric lighting, by opening the shading device(s), or both, between the first and second discomfort glare evaluations. Modifying the lighting conditions can lead to biased subjective assessments, as shown in the pilot study (Subsection 4.1.9).



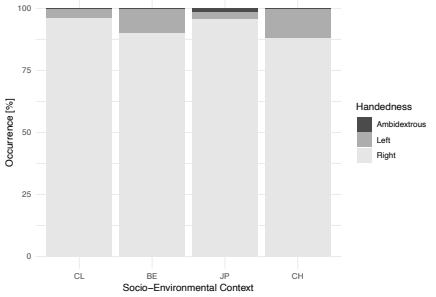
(a) Age



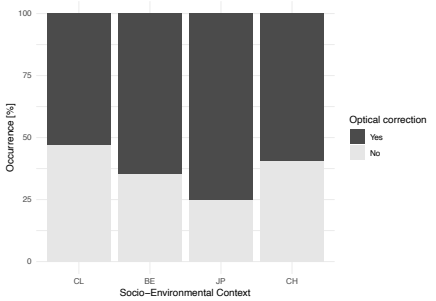
(b) Self-assessed glare sensitivity



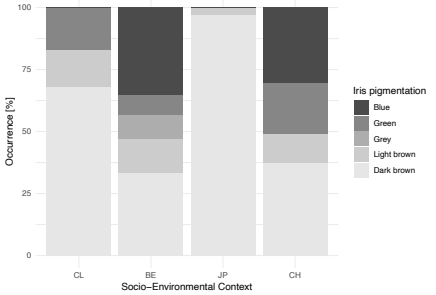
(c) Gender



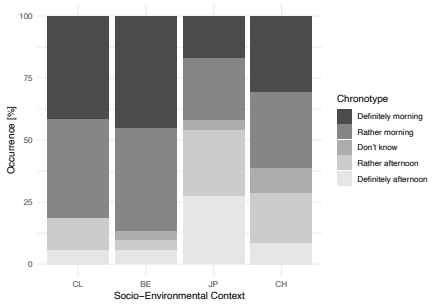
(d) Handedness



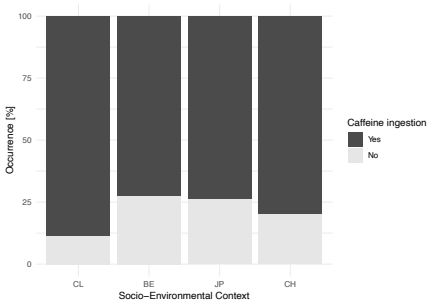
(e) Optical correction



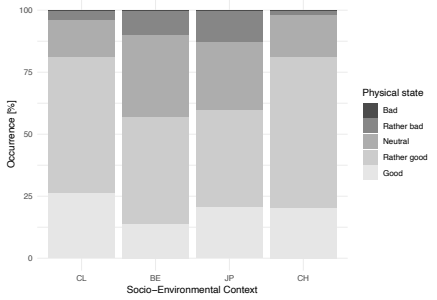
(f) Iris pigmentation



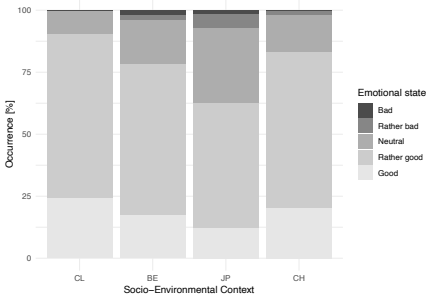
(g) Chronotype



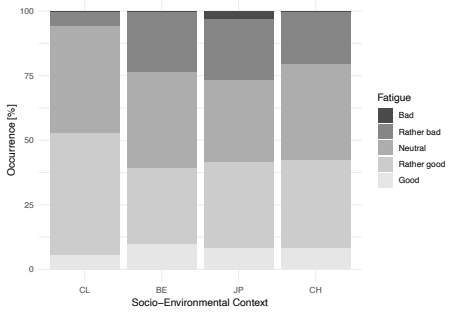
(h) Caffeine ingestion



(i) Physical state

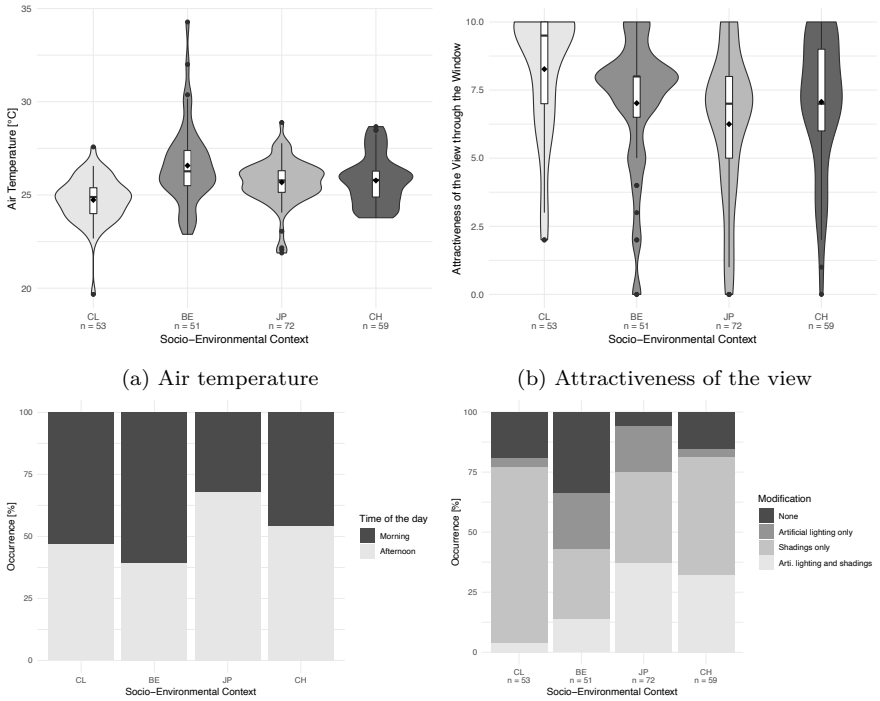


(j) Emotional state



(k) Fatigue

Figure 6.2: Violin plots, representing the density of the data, and box plots, representing the distribution of the data, or bar plots, representing the distribution of the data, for the baseline variables related to the subject in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers



(a) Air temperature

(b) Attractiveness of the view

(c) Time of the day

(d) Lighting conditions modification

Figure 6.3: Violin plots, representing the density of the data, and box plots, representing the distribution of the data, or bar plots, representing the distribution of the data, for the baseline variables related to the environment in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

A visual inspection of the plots in Figures 6.2 and 6.3 leads to hypothesize that in general, the distributions of the baseline characteristics are relatively balanced between the four socio-environmental contexts. However, three baseline variables, namely the iris pigmentation of the subject, the chronotype of the subject, and the attractiveness of the view through the window, seem to require a more thorough analysis, as an imbalance can be visually detected in their plot. These three variables are further discussed in Subsection 6.2.2.

6.2.2 Discussion

In Figure 6.2f, the Chilean and Japanese contexts have a much larger proportion of dark-colored eye subjects than the European ones. This observation is a common fact. The iris pigmentation variable could not have been balanced between the four socio-environmental contexts since it is an inherent (genetic) characteristic of the natives in each context. The imbalance observed between the four groups is identical to the imbalance existing between the four populations. Furthermore, some researchers suggest that the difference in iris pigmentation distributions between populations might be partly linked to selection pressure in response to an environmental factor, daylight [Sturm et al. 2012].

Although literature is inconclusive on the influence of iris pigmentation on discomfort glare perception (Chapter 2), the iris pigmentation might be a confounding variable when studying the influence of socio-environmental context on discomfort glare perception. This variable therefore has to be included in the analyses, and will be investigated in more detail in Chapter 7.

The imbalance in chronotype distributions might also be an inherent characteristic of the socio-environmental groups. A larger proportion of people feeling more alert and active in the afternoon, as observed for the Japanese socio-environmental context (Figure 6.2g), might be induced by a specific lifestyle or by some environmental factors, and therefore be intrinsic to a specific socio-environmental context. For instance, some studies show that chronotype might be related to geographical location and climate [Leocadio-Miguel et al. 2017; Randler 2008; Randler et al. 2014]. More specifically, the people with the latest chronotype were located in subtropical climate regions, which is in line with the observation made for Japanese subjects living in a humid subtropical climate [Randler 2008]. Consequently, the imbalance would not be due to a randomization issue, but would be representative of an imbalance existing between the selected socio-environmental populations.

It should, however, be noted that in this study, the chronotype was self-assessed by the subjects, and their subjective assessment might

not be representative of the intrinsic genetic characteristic called chronotype. In any case, since it is suggested that chronotype might be influencing discomfort glare perception [Kent et al. 2015b], the chronotype has to be also included in the analyses as a potential confounding variable, and will be investigated in more detail in Chapter 7.

At last, an imbalance in the attractiveness of the view through the window is observed, with Chilean subjects being more satisfied with the view through their window than other subjects (Figure 6.3b). In contrast to the iris pigmentation and the chronotype, this imbalance is most likely related to the selection of the office buildings. The buildings to which the investigator had access in Chile were imposing governmental buildings, located in areas where other office buildings had relatively few stories. Especially in Punta Arenas, the two buildings in which the study took place were probably the tallest in the city. The offices located next to the window in these buildings offered therefore unobstructed view to their occupants, similar to Figure 6.4.



Figure 6.4: Visual scene of the Chilean dataset showing the view through the window of an office in Antofagasta

The office buildings in which the study took place in Belgium, Switzerland, and Japan were average in height compared to their neighboring buildings, offering therefore less unobstructed views

through the window. In consequence, an imbalance in the attractiveness of the view through the window was unintentionally created. Since the literature is inconclusive on the influence that the view through the window might have on discomfort glare perception (Chapter 2), this variable has to be included in the analyses, and will be investigated in more detail in Chapter 7.

The comparison of the distributions of the other baseline variables, as well as of the five daylight discomfort glare metrics, does not seem to show any large imbalance between the four socio-environmental contexts. Nonetheless, some small differences can still be detected. In Chapter 7, the variables having a likely influence on discomfort glare perception based on the literature review will be investigated in more detail to remove any ambiguity over potential confounding effects. These potential confounding variables include for instance the age and the air temperature, of which the distributions still show some differences when their plots (Figures 6.2a and 6.3a) are closely inspected.

6.3 Applicability of the Discomfort Glare Metrics

Before looking for differences in discomfort glare perception between the four socio-environmental contexts, the efficiency of the daylight discomfort glare metrics in predicting discomfort glare perception needs to be tested.

In other words, the first step consists in analyzing how accurately the existing metrics can evaluate discomfort glare perception from daylight in each context. The goal is to establish whether the five selected metrics can be used in the four contexts to predict the subjective assessments of discomfort glare.

6.3.1 Analyses and Results

Two statistical methods are applied to evaluate the efficiency of the five daylight discomfort glare metrics for the four socio-environmental contexts: the Spearman's rank correlation (Subsection 4.5.3), and the ROC curve analysis (Subsection 4.5.4). For these analyses, the subjective assessment made on the 4-point glare scale A is the dependent variable, as originally planned, and the five daylight discomfort glare metrics are the independent variable, each in turn.

The socio-environmental context is not considered as an independent variable, but the analyses are applied separately for each socio-environmental context. Four datasets are therefore derived from Table 4.5, of which the E_v outliers have been removed, corresponding to each socio-environmental context (Table 6.1).

Firstly, a Spearman's rank correlation is applied instead of a Pearson's one since the correlation is evaluated between a continuous variable (each of the five metrics) and an ordinal variable (4-point glare rating scale A), as explained in Subsection 4.5.3.

The Spearman's correlation coefficients for each socio-environmental context between each daylight discomfort glare metric and the 4-point glare rating scale A are shown in Table 6.2.

Dataset	N	Discomfort on 4-point scale A			
		None	Small	Mod.	Large
CL	50	20	24	5	1
BE	48	28	8	8	4
JP	70	33	26	6	5
CH	58	21	21	11	5

Table 6.1: Information on the datasets (E_v outliers removed) used for the analyses of the applicability of the metrics (Section 6.3) and of the difference in discomfort glare perception between the socio-environmental groups (Section 6.6)

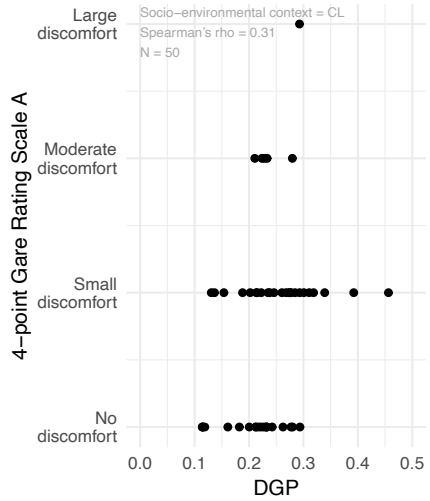
Socio-environmental context	Spearman's ρ				
	DGP	CGI	DGI	E_v	L_{mean}
CL	0.314	0.301	0.249	0.359	0.381
BE	0.421	0.373	0.377	0.444	0.453
JP	0.056	0.092	0.087	0.046	0.051
CH	0.491	0.529	0.528	0.428	0.418

Table 6.2: Spearman's ρ correlation coefficients between each metric and the 4-point glare rating scale A for the four socio-environmental groups

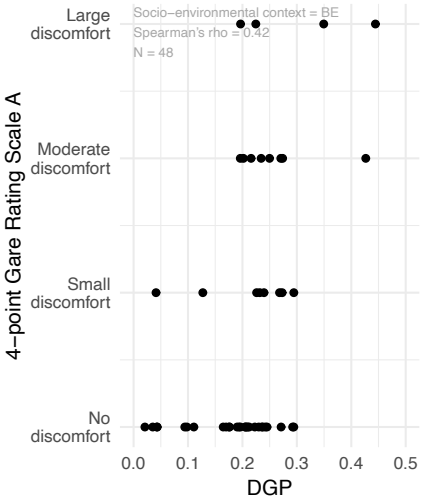
Using Ferguson's effect size benchmarks, the correlations for the Chilean, Belgian, and Swiss contexts are observed to show a practically significant effect, with some of them even approaching a moderate effect. By contrast, the correlations between the glare rating scale A and the five metrics in the Japanese context lie around 0, which means that the effect size is almost null and not practically relevant.

To visualize the correlations between the daylight discomfort glare metrics and the ratings on the 4-point scale A for each context, scatter plots have been generated. In Figure 6.5, the scatter plots related to the DGP are displayed for the four socio-environmental contexts. The scatter plots related to the other metrics are available in Appendix G. It should be noted that the Spearman's rank correlation coefficients are calculated on the ranks and not on the absolute values of the variables.

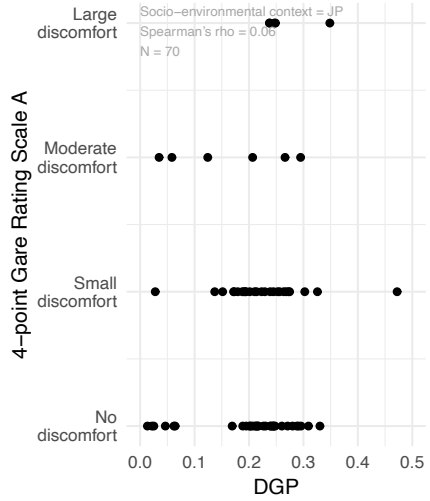
Secondly, ROC curve analyses are also conducted for each of the four socio-environmental contexts, and each of the five daylight discomfort glare metrics. As explained in Subsection 4.5.4, this



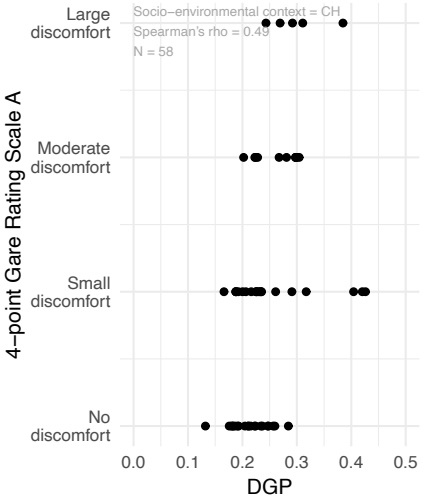
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context



(c) Japanese socio-environmental context



(d) Swiss socio-environmental context

Figure 6.5: Scatter plots of the ratings on the 4-point glare rating scale A in function of the DGP values for the four socio-environmental groups

analysis method is used to evaluate the diagnostic ability of a binary classifier model. The five metrics are therefore the binary classifier models, with all the metric values located below a certain cut-off considered as no discomfort due to glare, and all the metric values located above as discomfort due to glare.

A subjective assessment in the form of a binary classifier is needed to evaluate the diagnostic performance of the metrics. One of the characteristics of the 4-point glare scale A is the presence of the "No/Yes" binary classifier in the labels of the scale, allowing to discriminate the assessments between "no discomfort due to glare" and "discomfort due to glare".

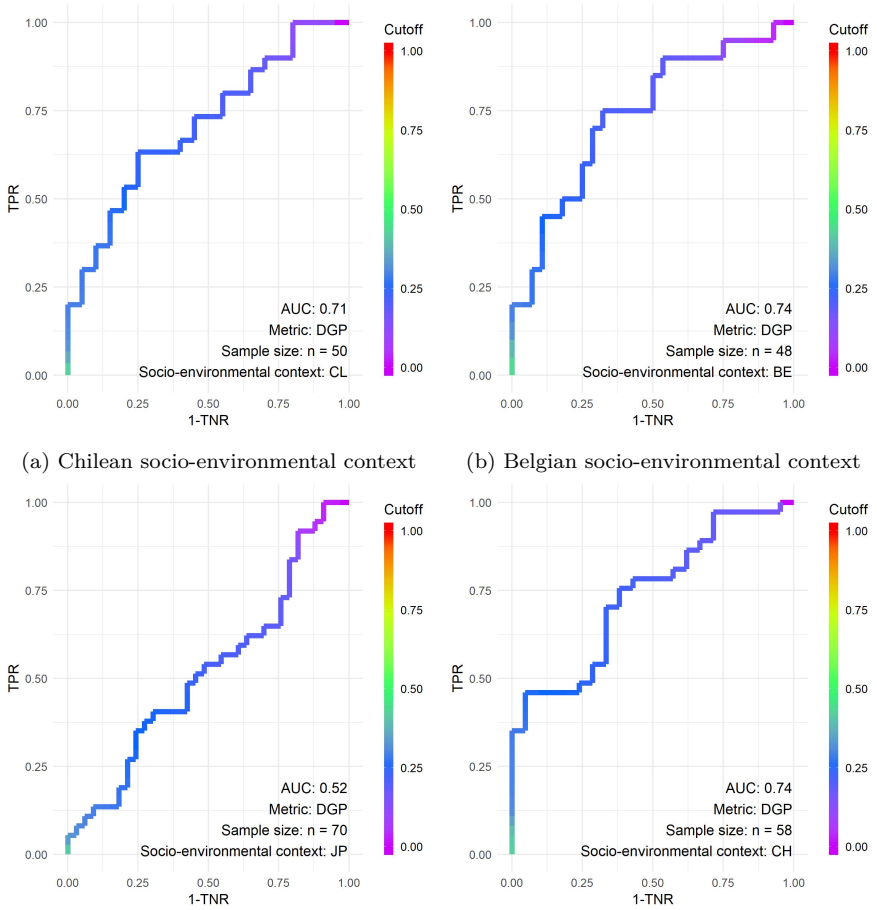
ROC curves and their corresponding AUC are computed for the five daylight discomfort glare metrics considered as binary classifier models, based on the binary transformation of the 4-point glare scale A. The AUC are displayed in Table 6.3. As the ROC curves and their respective AUC appear to be similar across the metrics for each context, only those related to the DGP are shown in Figure 6.6. The ROC curves related to the other metrics are available in Appendix G.

Socio-environmental context	AUC				
	DGP	CGI	DGI	E_v	L_{mean}
CL	0.71	0.70	0.67	0.72	0.72
BE	0.74	0.71	0.72	0.74	0.74
JP	0.52	0.55	0.55	0.51	0.51
CH	0.74	0.76	0.76	0.69	0.67

Table 6.3: AUC values derived from the ROC curve analyses of the performance of each of the five discomfort glare metrics to predict the binary transformation of the ratings on the 4-point glare rating scale A in the four socio-environmental groups

By visually inspecting the ROC curves for the DGP (Figure 6.6), the curve of the Japanese context is observed to be relatively flat compared to that of the other contexts. This observation is confirmed by the AUC of the Japanese curve, which is around 0.5, against an AUC of around 0.7 for the others.

When the AUC benchmarks found in the literature (Subsection 4.5.4) are applied to these results, the DGP appears to be an ac-



(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

Figure 6.6: ROC curves from the analyses of the performance of the DGP to predict the binary transformation of the ratings on the 4-point glare rating scale A for the four socio-environmental groups

ceptable model to discriminate between visually discomforting and not discomforting scenes in the Chilean, Belgian, and Swiss contexts, but fails the discrimination in the Japanese context.

6.3.2 Discussion

Since the two independent analyses produced similar results, it can be assumed that these statistical tests are reliable.

First of all, and surprisingly, the subjective assessments of the Japanese socio-environmental group on the 4-point glare scale A cannot be evaluated by the daylight discomfort glare metrics. The correlation coefficients for the five metrics are below the threshold of practical significance, and the AUC indicate that the five metrics fail in diagnosing the subjective assessments between "no discomfort due to glare/discomfort due to glare". The ROC curves of the Japanese socio-environmental group follow a diagonal line (Figure 6.6c), meaning that there is a probability of around 0.5 that a randomly selected discomforting scene has a higher DGP value than a randomly selected non-discomforting scene, which is equivalent to a random discrimination.

Regarding the other three socio-environmental groups, the subjective assessments can be predicted with slightly varying efficiency, but the results of each context pass the threshold of practical significance for the Spearman's rank correlation, and are not failing in the ROC curve analysis. The subjective assessments of the Swiss group are on average better predicted than those of the Belgian group, as can be deduced from the higher correlation coefficients in the Swiss context (Table 6.2). In turn, the subjective assessments of the Belgian group are better predicted than those of the Chilean group, as shown by the correlation coefficients.

These results could imply that the daylight discomfort glare metrics are somewhat more efficient for European socio-environmental contexts than for other socio-environmental contexts. However, it should be noted that, since the Chilean data were collected in three different cities and were the first data to be collected by the investigator, this dataset is expected to be noisier than the other ones.

More noise in the Chilean dataset could explain the slightly lower correlation coefficients compared to the European ones. Furthermore, the Belgian data was collected in seven different buildings, against four buildings in Switzerland. This difference might also result in a Belgian dataset a bit noisier than the Swiss one, and therefore lower correlation coefficients.

The results of this section are hardly comparable to similar results from the literature. The ROC curve analysis has only recently been introduced in the field of discomfort glare research [Rodriguez et al. 2016a], and no field study in this field has yet reported this type of result. Regarding the correlation coefficients, the only ones published in the literature that are based on data from a field study were calculated on the percentage of discomfort for binned data rather than on the raw subjective assessments made by the subjects [Hirning et al. 2014].

The results can, however, be compared to those of laboratory studies, and especially to those of a recent meta-analysis study combining data from several laboratory studies [Wienold et al. 2019]. The mean correlation coefficients of six laboratory studies for the five daylight discomfort glare metrics studied in this case are between $\rho = 0.48$ (DGI) and $\rho = 0.56$ (DGP). In this field study, the mean correlation coefficients are between $\rho = 0.38$ (DGI) and $\rho = 0.41$ (DGP) if the data from the Japanese context are excluded. Furthermore, the mean AUC lies around 0.8 for the laboratory studies, against around 0.72 in this study excluding the data from the Japanese context.

The better performance of the metrics to predict the subjective assessments made in the laboratory studies is assumed to be mainly related to the noise inherent to field studies. A lot of extraneous variables can have a confounding effect, affecting the results. These extraneous variables are much better controlled in laboratory studies, reducing their potential influence.

However, other explanations are also possible to explain the difference in the performance of the metrics between the field and laboratory studies, such as the difference in the subjective assess-

ment methods used between the field and laboratory studies in this case. To further investigate this difference, additional analyses will be conducted in Sections 8.2 and 8.3 respectively on the subjective assessment methods and the difference between the results of field and laboratory studies.

Finally, both the correlation coefficients and the AUC indicate that the contrast-based metrics, namely the CGI and DGI, are slightly more efficient for the Swiss socio-environmental context, whereas the saturation-based metrics, namely the E_v and L_{mean}, produce better results for the Chilean and Belgian contexts. Since the visual scenes were selected in order to produce saturation glare, it was expected that saturation-based metrics would perform better in the four contexts. Moreover, the lighting levels are on average a bit brighter in the offices of the Swiss socio-environmental context.

To further investigate the different performance of the contrast-based and saturation-based metrics, the difference in the correlation coefficients is tested with the R package *cocor* version 1.1-3 [Diedenhofen et al. 2015]. The cocor test evaluates whether the correlation coefficients of the CGI and DGI for the Swiss socio-environmental context are significantly larger than those of the E_v and L_{mean}, and inversely for the Belgian and Chilean contexts. A Bonferroni correction is applied for the tests ($\alpha = 0.0125$) since the comparison is made between the four metrics in each context. Moreover, the alternative hypothesis is one-sided.

The results of the tests show that the null hypothesis is retained for the three contexts and for the four metrics. Hence the difference between the correlation coefficients seems not to be statistically significant (p-values > 0.045). Although the difference in this study might be due to the relatively small dataset and is not statistically meaningful, more research on this topic might be useful to define which type of discomfort glare occurs in which conditions, and which type of metrics should be used.

In conclusion, the five daylight discomfort glare metrics are reasonable models to predict the subjective assessment made on the 4-point glare rating scale A of the Chilean, Belgian, and Swiss so-

cio-environmental groups. In these contexts, there is a probability of around 0.72 that a randomly selected discomforting scene has a higher DGP value than a randomly selected non-discomforting scene.

None of the metrics are, however, efficient to predict the subjective assessment made on the 4-point glare scale A of the Japanese socio-environmental group. This unexpected result is therefore further analyzed in the following section.

6.4 Investigation of the Japanese Assessments

Given the results in the previous section, the subjective assessments of the Japanese socio-environmental group are investigated more deeply. The non-efficiency of the metrics into predicting the subjective assessments of the Japanese group made on the 4-point scale A might be caused by some kind of experimental bias.

On the one hand, response biases, such as socially desirable responding or acquiescence response style, could distort the subjective assessments. Since the study protocol and questionnaire were similar in the four contexts, the presence of response bias in only one of the contexts is not likely.

However, several studies have shown that some response biases are linked to cultural dimensions [Smith 2004; Watkins et al. 1995; Johnson et al. 2005], demonstrating that a specific response bias might play a role in one socio-environmental context but not in the others.

On the other hand, the subjective assessments might be irrelevant due to the misunderstanding or the inappropriateness of the question in one of the socio-environmental contexts, especially since the questionnaire had to be translated.

In this section, analyses are conducted to investigate whether these study biases might have distorted the subjective assessments of the Japanese socio-environmental group, making them unpredictable by the daylight discomfort glare metrics.

6.4.1 Analyses and Results

First, the six most common response biases [Wetzel et al. 2016] are considered one by one. The analyses show no evidence that one of them has distorted the subjective assessments made by the Japanese socio-environmental group. This finding is explained in further details for each response bias:

- acquiescence and disacquiescence response styles (1 and 2)
  Since neither the question nor the multiple-choice responses

required the subject to express an agreement or disagreement, these response biases cannot have influenced the subjective assessments.

- careless responding (3)
  Although inattentive responding could have occurred, this issue was partly controlled through the visual task score. The mean score of the subjects of the Japanese socio-environmental context for the visual task, calculated according to Equation 4.9, is 99.4%. This result implies that the subjects were correctly reading the questions.
- extreme response style (4)
  Subjects' subjective assessments might have been corrupted by a preference for extreme categories. In the 4-point glare rating scale A, the extreme category is Yes, a large discomfort, since it is a uni-polarized scale. Only five subjects of the Japanese socio-environmental group (7%) chose this category, indicating that bias from the extreme response style is unlikely.
- midpoint response style (5)
  Instead of extreme categories, subjects' assessments might have been corrupted by a preference for the midpoint of a rating scale. Since the 4-point scale A does not have a midpoint, bias from the midpoint response style cannot be justified.
- socially desirable responding (6)
  Complaining, in this case about discomfort glare, might be seen as socially undesirable, and in disagreement with social norms and rules in a specific socio-environmental context. If socially desirable responding had played a role in the subjective assessments given by the subjects of the Japanese socio-environmental context, there would have been a different proportion of data points in the four response categories (Table 6.1) for the Japanese group than for the three other groups, with significantly fewer points in the higher categories.
  A χ^2 test is applied to evaluate whether the proportions in the four groups are the same (Table 6.4). The significance level for this test is $\alpha = 0.05$ since the five daylight discomfort

glare metrics are not involved and the test is applied only once for each rating category. No statistically significant difference is observed with the Japanese group. Hence the hypothesis that socially desirable responding has biased the subjective assessments of the Japanese group is not supported.

Response category	χ^2 ($df = 3$)	p-value	Significant difference
No discomfort	6.95	0.074	None
Small discomfort	9.97	0.019*	CL × BE
Moderate discomfort	3.76	0.289	None
Large discomfort	2.68	0.443	None

Table 6.4: Results of the χ^2 test for equality of proportions of the subjective assessments on the 4-point glare rating scale A between the four socio-environmental groups

Secondly, the subjective assessments of the Japanese socio-environmental group made through two other subjective assessment methods, which are also glare rating scales but with different labels and questions, are analyzed. By comparing the performance of the metrics to predict the other subjective assessments rather than the ones made on glare scale A, the analyses test whether the subjective assessments made on glare scale A might have been biased due to the inaccuracy or the inappropriateness of the question or labels in the Japanese version of the questionnaire.

Spearman's rank correlations are evaluated between the five metrics and the 5-point glare rating scale B, and between the five metrics and the 4-point glare rating scale C. As a reminder, the 4-point scale C was only added for the parts of the study conducted in Japan and in Switzerland.

5-point glare rating scale B	4-point glare rating scale C
Intolerable	Intolerable
Uncomfortable	Disturbing
Acceptable	Noticeable
Perceptible	Imperceptible
Imperceptible	

The correlation coefficients for the Japanese socio-environmental

context between each metric and the glare rating scales B and C are shown respectively in Tables 6.5 and 6.6.

Socio-environmental context	Spearman's ρ				
	DGP	CGI	DGI	E_v	L_{mean}
CL	0.345	0.260	0.191	0.369	0.370
BE	0.332	0.305	0.337	0.348	0.367
JP	0.143	0.153	0.068	0.123	0.142
CH	0.255	0.277	0.318	0.236	0.215

Table 6.5: Spearman's ρ correlation coefficients between each metric and the 5-point glare rating scale B for the four socio-environmental groups

Socio-environmental context	Spearman's ρ				
	DGP	CGI	DGI	E_v	L_{mean}
JP	0.216	0.246	0.198	0.208	0.194
CH	0.455	0.520	0.520	0.393	0.408

Table 6.6: Spearman's ρ correlation coefficients between each metric and the 4-point glare rating scale C for the Japanese and Swiss socio-environmental groups

To demonstrate that the poor performance of the metrics to predict the subjective ratings on glare scale A in the Japanese context was due to a bias in the subjective assessment method, higher correlation coefficients, comparable to those of the other socio-environmental contexts, were expected between the metrics and the subjective assessments made through the two other methods.

In Table 6.5, the correlation coefficients of the Japanese group still do not show a practically relevant effect when compared against Ferguson's benchmarks, although a slight increase can be observed between these coefficients and those for the glare scale A. In contrast, almost all the correlation coefficients for the three other contexts are above the minimal benchmark for practical relevance.

In Table 6.6, the correlation coefficients of the Japanese group just exceed the benchmark for practical relevance, and are again a bit larger than those for glare scale B. However, these coefficients are still more than two times smaller than the correlation coefficients of the Swiss group, which show a small to moderate effect.

Lastly, the subjective assessments of the Japanese group made

through the OEQ is analyzed and compared to those of the other socio-environmental groups. A binary variable, called the "Glare report", has been generated from the analysis of the OEQ answers (Subsection 4.2.3). Four datasets are therefore derived from Table 4.6, of which the E_v outliers have been removed, corresponding to each socio-environmental context (Table 6.7).

Dataset	N	Binary glare report	
		No	Yes
CL	51	29	22
BE	46	30	16
JP	69	43	26
CH	58	29	29

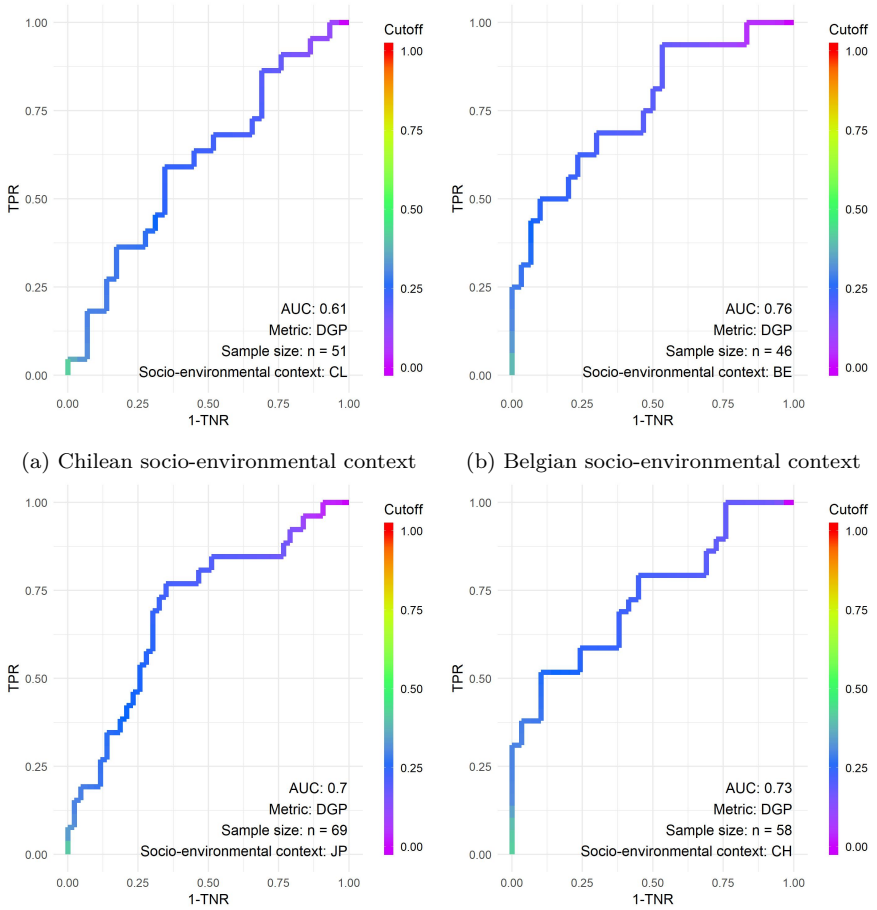
Table 6.7: Information on the datasets (E_v outliers removed) used for the analysis of the Japanese subjective assessments (Section 6.4)

Using these four datasets, ROC curves and their corresponding AUC are computed for each socio-environmental context, considering the five daylight discomfort glare metrics as the binary classifier models, and the binary glare report from the OEQ as the subjective assessment. The AUC are displayed in Table 6.8. As the ROC curves and their respective AUC appear to be similar across the metrics for each context, only those related to the DGP are shown in Figure 6.7. The ROC curves related to the other metrics are available in Appendix G.

Socio-environmental context	AUC				
	DGP	CGI	DGI	E_v	L_{mean}
CL	0.61	0.6	0.58	0.61	0.63
BE	0.76	0.76	0.76	0.75	0.73
JP	0.7	0.71	0.68	0.68	0.68
CH	0.73	0.72	0.71	0.72	0.71

Table 6.8: acrshortAUC values derived from the ROC curve analyses of the performance of each of the five discomfort glare metrics to predict the binary glare report in the four socio-environmental groups

A visual inspection of the graphs in Figure 6.7 indicates that in addition to the Belgian and Swiss ROC curves bending towards the upper left corner, the ROC curve for the Japanese group is not



(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

Figure 6.7: ROC curves from the analyses of the performance of the DGP to predict the binary glare report in the four socio-environmental groups

following the diagonal any more and has a similar tendency. The AUC values for these three contexts are in the range of 0.68 to 0.76, which means that the DGP is an acceptable model to discriminate between visual scenes with No glare report and Glare report when interpreted against the benchmarks available in the literature.

Conversely, the AUC for the Chilean group decreased and its ROC curve became flatter (Figure 6.7a). The comparison of the AUC values for the Chilean group against the benchmarks indicates that the metrics tend to fail to discriminate between the visual scenes for which glare has been reported and those with no report of glare.

6.4.2 Discussion

From the results of the analyses, it is assumed that the inefficiency of the daylight discomfort glare metrics to explain the subjective assessments made on the 4-point glare rating scale A of the Japanese socio-environmental group cannot be justified by the response biases mentioned previously.

Furthermore, the correlation coefficients of the Japanese group with the two other glare rating scales (B and C) are still below or at the limit of practical significance ($\rho < 0.2$ and $\rho \approx 0.2$). However, a slight improvement of the correlation coefficients of the Japanese group is observed. The subjective assessments made on the 5-point scale B are better predicted than those made on the 4-point scale A. The assessments on the 4-point scale C lead to the largest correlation coefficients.

One hypothesis to explain this improvement is that the use of different sets of labels might have improved the results, as the labels of the 4-point scale A were not correctly understood by the Japanese socio-environmental group. However, this hypothesis cannot explain all the difference. First, the correlation coefficients of the Japanese group are still low compared to the other groups. Second, the correlation coefficients based on the 5-point and 4-point glare rating scales (B and C) for the three other socio-environmental groups are generally lower than those based on the 4-point scale A, which is contrary to the suggested hypothesis.

Since the results for the Japanese group in Section 6.3 cannot be explained by response biases or by some misunderstanding of the labels of the glare rating scale A, the question asking to rate glare on a scale might be the source of the problem. Therefore, the alternative subjective assessment made through the OEQ was analyzed. In the ROC curve analysis using the binary glare report, the AUC for the Japanese group rose to around 0.7, against around 0.5 when the binary transformation of the 4-point scale A was used. This result means that the five daylight discomfort glare metrics can actually reasonably diagnose the reporting of discomfort due to glare in the Japanese context.

Since the binary glare report is much better predicted by the metrics than the assessments made on the glare rating scales in the Japanese context, it is hypothesized that the questions asking to rate discomfort glare on the scales were not correctly understood. A potential explanation is that the subjects of the Japanese context did not understand what they had to rate, making their assessments on the glare rating scales incoherent and hardly predictable by the metrics.

More specifically, it is assumed that the term that was used to refer to discomfort glare in the Japanese version of the questionnaire was not appropriate.

To understand this issue, some basic knowledge of the Japanese language is required. There exist two alphabets in Japanese:

- hiragana, to phonetically spell out Japanese words
- katakana, to phonetically spell out foreign words

Because of these two alphabets, glare can be referred to in two ways:

まぶしさ	グレア
[mabushisa]	[gerea]

Table 6.9: The word “glare” in hiragana (left) and katakana (right) alphabets

From a discussion with a native Japanese speaker, who was not familiar with the lighting field, the difference between the two terms is explained by the fact that "gerea", which is the phonetic spelling out of the English word "glare" in Japanese, is mainly used and understood by experts and people working in the field, whereas "mabushisa", which is the phonetic spelling out of the Japanese word for glare, is understood by people in general. However, it seems that "mabushisa" does not have the exact same meaning as "gerea", and is generally related to disability glare.

In the questions asking for an assessment of discomfort glare on the scales, the word "gerea" in Japanese was used instead of "mabushisa" in order to provide a faithful translation of the original questionnaire. This decision was also made because of the presence of a definition of the term "gerea" below each question mentioning it.

It is hypothesized that the subjects of the Japanese context did not understand the term "gerea", as it is a rather technical term in Japanese, and did not take the time to read the definition provided. Therefore, their subjective assessments made on the 4-point glare rating scale A are assumed to be affected by the bias of careless responding.

Moreover, it is assumed that the correlation coefficients get higher with each consecutive glare rating scale because of some kind of learning bias. As the same question asking about "gerea" returns with each glare scale, more subjects are inclined to read the description provided for the term "gerea" and answer knowingly.

From the evidence collected in the data analyzed, only the subjective assessment made through the OEQ leads to the detection of a practically significant correlation with the five discomfort glare metrics. Therefore, the statistical analyses to look for the influence of the socio-environmental context or other factors on discomfort glare perception will be based only on this subjective assessment method for the Japanese dataset.

Finally, an unexpected result arises from the ROC curves and corresponding AUC values for the Chilean socio-environmental context. The AUC for that group dropped to around 0.6. According to

the benchmarks, this low value implies that the five daylight discomfort glare metrics can hardly discriminate between visual scenes with and without glare report in the Chilean context. This result is surprising as the subjective glare assessments of the Chilean group made on the glare rating scales were relatively efficiently predicted by the metrics. Further investigation of this issue is therefore performed in the next section.

6.5 Investigation of the Chilean Assessments

In Section 6.3, the metrics show an AUC of around 0.7 for the Chilean group, which means that there is a probability of around 0.7 that the discomfort glare metric value measured for a randomly selected discomforting scene in the Chilean context is larger than the discomfort glare metric value measured for a randomly selected non-discomforting scene in the same socio-environmental context. This result classifies the metrics as acceptable models to explain discomfort glare perception from daylight in the Chilean socio-environmental context.

In Section 6.4, in which the binary glare report is used as the subjective assessment, the AUC drops to around 0.6 for the Chilean group. The metrics then become weak, even failing models to predict discomfort glare perception in the Chilean context, according to the benchmarks given in Subsection 4.5.4.

This section aims at explaining the inconsistency between the results based on the subjective assessments made via the glare rating scales and those made via the OEQ for the Chilean socio-environmental group.

6.5.1 Analyses and Results

Since the values of the daylight discomfort glare metrics did not change between the analyses in Section 6.3 and Section 6.4, it is hypothesized that the inconsistency of the AUC values for the Chilean group comes from a divergence in the subjective assessments made via the two different methods. The reliability of the different subjective assessment methods used in the questionnaire, namely their ability to measure consistently what they are intended to measure, can be objectively evaluated through the Cronbach's α [Tavakol et al. 2011].

A Cronbach's α test is conducted for each socio-environmental context between the binary glare report generated from the OEQ and the binary transformation of the 4-point glare scale A. As seen in Table 6.10, the test results are below the minimal recommended

value for internal consistency of 0.8 [Nunnally et al. 1994], i.e., the threshold at which both variables can be said to measure the same concept, for both the Japanese and Chilean socio-environmental groups.

Socio-environmental context	Cronbach's α	95% Confidence Interval (CI)
CL	0.756	$[0.62 - 0.89]$
BE	0.862	$[0.78 - 0.94]$
JP	0.732	$[0.60 - 0.86]$
CH	0.827	$[0.74 - 0.92]$

Table 6.10: Results of the Cronbach's α tests for internal consistency between the binary glare report and the binary transformation of the 4-point scale A in the four socio-environmental groups

This result was expected for the subjects of the Japanese group, since it was observed in the previous section that they might have not correctly understood what they were asked to assess in the questions with glare rating scales.

Regarding the subjects of the Chilean group, it is hypothesized that they understood what "deslumbramiento" referred to in the questionnaire, i.e., glare, as this word was used in their answers to the OEQ. Moreover, the correlations of the metrics with the subjective assessments made on the glare rating scales show practically relevant effects, which suggest that the Chilean subjects' interpretation of "deslumbramiento" matched what the metrics are supposed to predict, namely discomfort glare perception.

However, since internal consistency is not achieved between the two subjective assessments (Table 6.10), it is hypothesized that the binary glare report does not reliably measure discomfort glare perception in the Chilean context. Either the translation or interpretation of the answers to the OEQ was not properly executed, distorting the information, or the OEQ was not correctly formulated or misinterpreted, leading to ambiguous answers.

The investigator recalled from discussions with subjects in the Chilean context, and especially in the northernmost Chilean city, Antofagasta, that daylight was highly associated with thermal discomfort.

Very often, the subject would explain that the shading devices had to stay closed to avoid thermal discomfort in the office. Overheating is most probably a very important issue in one of the cities of the world having the largest annual sum of direct normal irradiation [Solargis 2010].

Bearing in mind the association between daylight and thermal discomfort, a second analysis of the answers to the OEQ of the Chilean group highlights several ambiguities:

- In the answers to the OEQ about dissatisfying elements in the lighting conditions, elements related to thermal conditions are mentioned, such as:

  Which element(s) bother(s) you in the current lighting conditions?

  – "*La calor y el reflejo del sol que me provoca ardor a la vista con indicaciones de lagrimas.*"
  [The heat and the reflection of the sun that causes my eyes to burn with signs of tears.]
  – "*El calor*"
  [The heat]

- In the answers to the OEQ about dissatisfying elements of the ambient temperature, elements related to daylight and visual conditions are mentioned, such as:

  Why is the ambient temperature not totally satisfying?

  – "*Porque el sol me está quemando la piel del brazo izquierdo y me molesta la vista*"
  [Because the sun is burning the skin of my left arm and bothers my vision]
  – "*Porque tengo calor y los rayos del sol inciden casi directamente sobre mi estación de trabajo*"
  [Because I'm hot and the sun rays hit almost directly my desk]

Although this observation was first made based on oral feedback from the subjects, the association between daylight and thermal

discomfort in the Chilean context can be clearly noticed in the answers. Therefore, it is hypothesized that the subjects in the Chilean context have mixed thermal and visual discomfort in their answers, since both are related to daylight in their mind.

Consequently, when a subject of the Chilean group is complaining about daylight or the sun in the answer to the OEQ, it might not mean that the sun or daylight is causing visual discomfort, although the question asks about satisfaction with lighting conditions. Instead, this answer might mean that the heat brought by the sun, and indirectly daylight, is the unsatisfactory element, causing the subject thermal discomfort. Unfortunately, with no other element given in the answer to the OEQ, the investigator classified these answers, i.e. those mentioning "sun" or "sunlight", as a report of discomfort glare from daylight.

Although this issue would require further testing based on an appropriate experimental design aimed at exploring the relationship between visual and thermal discomfort in the Chilean context, further analyses are conducted to see whether the hypothesis is somehow supported by the data.

For this purpose, the data points for which the answer to the OEQ exhibits a visual/thermal discomfort ambiguity are removed from the dataset of the Chilean socio-environmental context. More specifically, the data points for which the answer to the OEQ was not empty are removed if:

- the reason for dissatisfaction given in the answer to the OEQ only refers to thermal discomfort (e.g. "*el calor*"), or
- the reason for dissatisfaction given in the answer to the OEQ refers to the sun, the window, or the light from outside, without mentioning the reason why this element is unsatisfactory (e.g. "*sol*", "*las persianas deja entrar luz de sol*", or "*La luz exterior*")

The removal of ambiguous data points was only applied to the Chilean dataset, as only the subjects from this context spontaneously associated daylight with overheating, but this association

could have biased subjective assessments in other contexts.

By applying these rules, nine data points are removed from the total Chilean dataset, but only four data points (8%) are removed from the dataset that is actually being used for the analyses. One of the removed data points was collected in Concepción, another one in Punta Arenas, and the two others in Antofagasta.

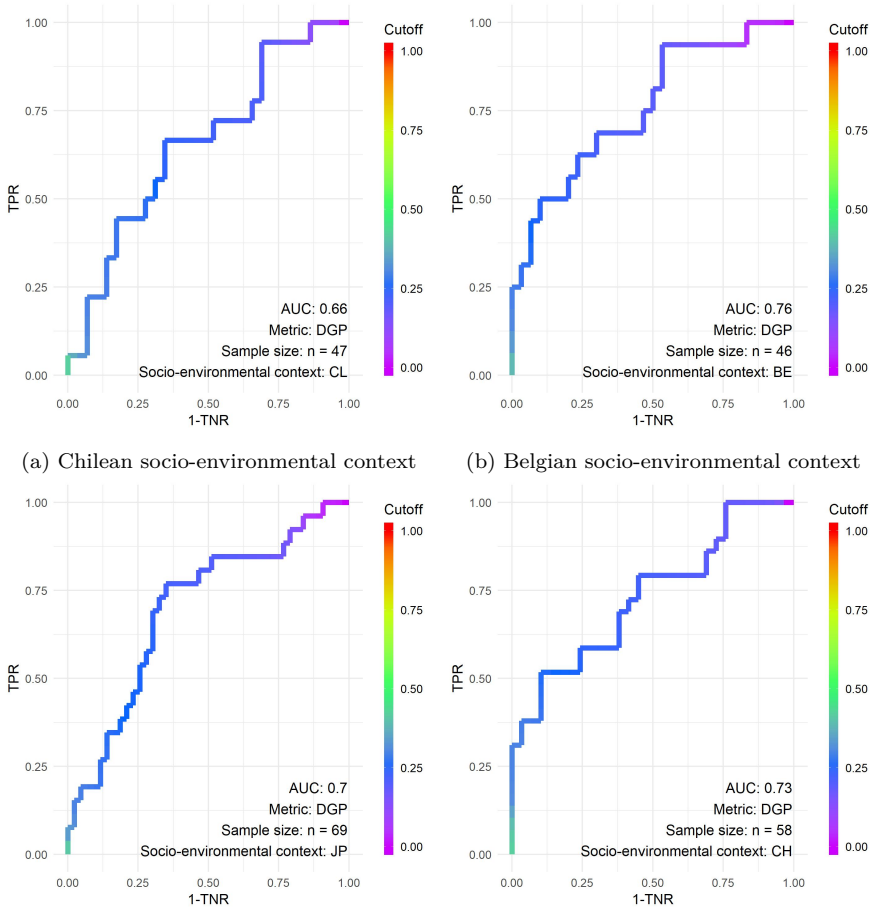
The Chilean dataset in Table 6.7 becomes the Chilean dataset in Table 6.11. Interestingly, for all but one removed data points, the answer to the OEQ about satisfaction with ambient temperature mentions that the subject felt too warm, sometimes relating the cause of it to daylight entering the building.

Dataset	N	Binary glare report	
		No	Yes
CL	47	29	18
BE	46	30	16
JP	69	43	26
CH	58	29	29

Table 6.11: Information on the datasets (E_v outliers and ambiguous data points removed) used for the analyses of the Chilean subjective assessments (Section 6.5) and of the difference in discomfort glare perception between the socio-environmental groups (Section 6.6)

ROC curves and their corresponding AUC are computed a second time with the modified dataset for the Chilean context for the five daylight discomfort glare metrics and the binary glare report. The AUC are displayed in Table 6.12. As the ROC curves and AUC appear to be similar across the metrics for each context, only those related to the DGP are shown in Figure 6.8. The ROC curves related to the other metrics are available in Appendix G.

Since the dataset and the variables of the ROC curve analysis did not change for the Belgian, Japanese, and Chilean groups, the results are still the same as those presented in Subsection 6.4.1. Regarding the results for the Chilean group, the removal of four data points (8%) with detectable ambiguous answers to the OEQ slightly modifies the ROC curve. The AUC of the Chilean socio-environmental group rises from around 0.6 to around 0.65.



(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

Figure 6.8: ROC curves from the analyses of the performance of the DGP to predict the binary glare report in the four socio-environmental groups when the ambiguous Chilean data points are discarded

Socio-environmental context	AUC				
	DGP	CGI	DGI	E_v	L_{mean}
CL	0.66	0.64	0.62	0.65	0.67
BE	0.76	0.76	0.76	0.75	0.73
JP	0.7	0.71	0.68	0.68	0.68
CH	0.73	0.72	0.71	0.72	0.71

Table 6.12: acrshortAUC values derived from the ROC curve analyses of the performance of each of the five discomfort glare metrics to predict the binary glare report in the four socio-environmental groups when the ambiguous Chilean data points are discarded

6.5.2 Discussion

The results of the previous subsection suggest that there is no internal consistency between the subjective assessments made on the 4-point glare rating scale A and those made through the OEQ for both the Japanese and Chilean socio-environmental groups. Regarding the Japanese group, the lack of consistency is hypothesized to be due to the word used for "glare" that might have not been understood by the subjects.

A deeper analysis of the answers to the OEQ was executed to understand the inconsistency between the subjective assessments made by the Chilean socio-environmental group. A qualitative analysis of the answers to the OEQ of the Chilean group led to the hypothesis that an association exists between daylight and thermal discomfort in the Chilean context.

By removing four ambiguous data points from the Chilean dataset, the AUC improve slightly. However, and as expected from only four data points removed, the AUC still do not pass the benchmark at which the daylight discomfort glare metrics can be considered as reasonable models to predict the binary glare report of the Chilean group. Even though the removal of four ambiguous cases causes a change of the AUC in the expected direction, this evidence is not enough to draw any conclusion on the lack of internal consistency between the subjective assessments in the Chilean context.

Nonetheless, these results suggest that some indoor environmental factors, such as visual and thermal factors, might interact. As

stated recently [Torresin et al. 2018], more research is required on the potential interactions between indoor environmental factors. Discomfort glare is one factor in a multi-sensory environment, and numerous other factors could affect occupants' discomfort glare perception. For instance, a study has already shown that subjects' tolerance to discomfort glare might vary when they are outside of their thermal comfort zone [Yamin Garretón et al. 2015]. For that purpose, further analyses are conducted in Section 7.4 to investigate the interaction between daylight discomfort glare and thermal factors.

6.6 Influence of the Socio-Environmental Context

In this section, the goal is to determine whether the socio-environmental context of a subject influences her/his discomfort glare perception from daylight, hence whether subjects from different socio-environmental contexts perceive discomfort glare from daylight differently. In this regard, the literature suggests that the sensitivity to discomfort glare varies in different socio-environmental contexts, hence discomfort glare is reported at different lighting levels or stimuli in different contexts.

In the previous sections, the five daylight discomfort glare metrics appeared to be reasonable models for predicting discomfort glare in the four studied socio-environmental contexts. However, the robustness of the prediction of the metrics varied depending on the subjective assessment method used in the Chilean and Japanese socio-environmental contexts.

Further analyses of the subjective assessments made on the glare rating scales in the Japanese context (Section 6.4) and of the subjective assessments made through the OEQ in the Chilean context (Section 6.5) led to the hypothesis that this data might be biased.

Since the subjective assessments made on the glare rating scales in the Japanese context cannot be predicted by the metrics, it is decided not to include that data in the analyses in this section. Discomfort glare perception in Japan can still be compared to the other contexts via the subjective assessments made through the OEQ.

Furthermore, the subjective assessments made through the OEQ by four subjects in the Chilean context are also not included in the analyses in this section, as there was some ambiguity in their answer.

Therefore, the analyses to test the difference in the sensitivity to discomfort glare between different socio-environmental contexts are partly based on the subjective assessments made through the 4-

point glare scale A, for which only the Chilean, Belgian, and Swiss contexts are compared, and partly based on the subjective assessments made through the OEQ, for which the four contexts are compared.

The analyses based on the subjective assessments made through the 4-point glare scale A use the datasets described in Table 6.1, with the E_v outliers and the data from the Japanese context removed. Those based on the subjective assessments made through the OEQ use the datasets described in Table 6.11, with the E_v outliers and four ambiguous Chilean data points removed.

6.6.1 Analyses and Results

Analyses based on the 4-point glare scale A

A visual inspection of Figure 6.1 suggests that the lighting conditions were relatively similar in the Chilean, Belgian, and Swiss socio-environmental contexts. Consequently, a Kruskal-Wallis test is first applied to test whether the subjective assessments made on the 4-point scale A vary based on the socio-environmental context. A Kruskal-Wallis test is chosen over a one-way independent-measures ANalysis Of VAriance (ANOVA), since the dependent variable is ordinal, i.e., the 4-point glare rating scale A, and does not meet the assumption of normality [Andy Field 2002]. From the Kruskal-Wallis test, no statistically significant differences ($\chi^2(df = 2) = 3.28$, p-value$= 0.194$) are found among the three socio-environmental contexts.

To take into account the lighting conditions, the second analysis looks at the difference, between the three contexts, of the mean metric values for each category of the 4-point scale A. Since the outliers in terms of lighting conditions have been removed from the dataset, mean metric values can be compared instead of median values. The mean metric value and its related standard error (i.e., the standard deviation divided by the square root of the sample size) for each category and each metric are first compared graphically across the socio-environmental contexts to detect a potential trend. For reasons of brevity, only the bar plots for the DGP are

illustrated in Figure 6.9. The bar plots for the other metrics are available in Appendix G.

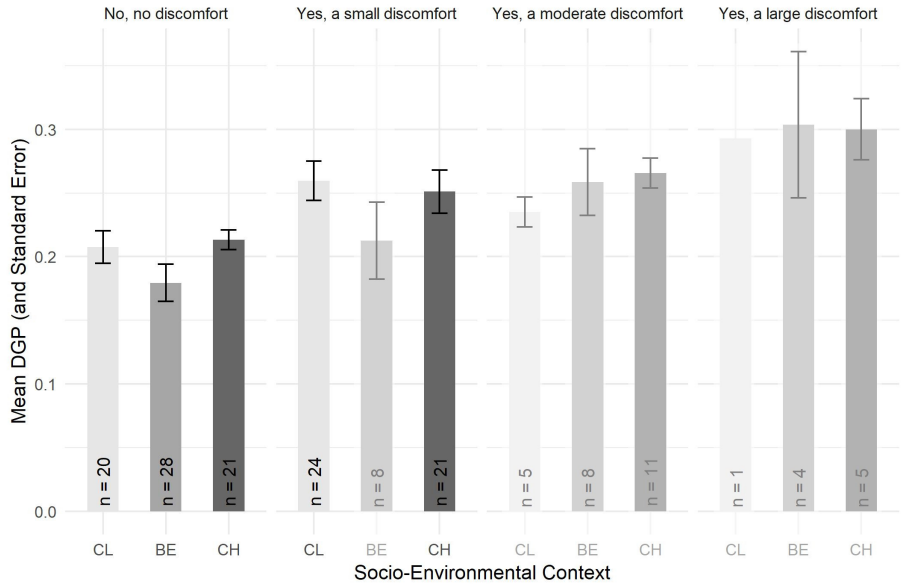


Figure 6.9: Bar plots of the mean DGP values for each category of the 4-point glare rating scale A for three socio-environmental groups; the bars based on less than 15 data points have been faded as the mean value of these bars should be considered carefully

The two central bar plots, i.e., those for the categories Yes, a small discomfort and Yes, a moderate discomfort, should be principally considered. This is because the mean values of the bar plots for the categories No, no discomfort and Yes, a large discomfort depend on extreme lighting conditions and on the occurrence of those extreme conditions in each context, and can therefore hardly be compared. Furthermore, the bars based on less than 15 data points are not reliable and should be interpreted with care.

In these conditions, there is not much information that can be learned from the bar plots comparing the mean metric values of each socio-environmental group for each category of the 4-point scale A.

To test whether the distribution of the metric values are signifi-

cantly different between the socio-environmental contexts for each category of the glare rating scale A, Kruskal-Wallis tests are applied separately for each category. A one-way independent-measures ANOVA could have been applied, but when verifying the assumptions, it appeared that the distributions within the groups (CL, BE, CH) were not always normally distributed. Therefore, the nonparametric equivalence of the one-way independent-measures ANOVA is applied.

The dependent variables of the Kruskal-Wallis tests are each of the five daylight discomfort glare metrics and the independent variable is the socio-environmental context. As a reminder, a Bonferroni correction has to be applied (corrected significance level of $\alpha = 0.01$) since the same hypothesis, namely that the distribution of the ranked metric values is the same in each socio-environmental context, is tested five times for the five daylight discomfort glare metrics. The results of the Kruskal-Wallis tests are shown in Table 6.13.

No statistically significant differences can be observed in Table 6.13 according to the corrected significance level.

However, it should be noted that, in some groups, the number of data points is small, such as in the Chilean group for the Yes, a large discomfort category. When a group size is small ($n < 5$), the test statistic does not properly follow a χ^2 distribution [McDonald 2014]. Moreover, with the application of the Bonferroni correction, there is a higher risk of Type II error. The results of these Kruskal-Wallis tests should therefore be interpreted carefully.

Finally, logistic regression analyses are used to test the influence of the socio-environmental context on discomfort glare perception. Several logistic regression analyses can be performed depending on the dependent variables (Section 4.5).

For the subjective assessments made on the 4-point scale A, the logistic regression model is described in Equation 6.1, with the metrics and socio-environmental context used as the independent variables. The dependent variable is ordinal (1 = No, no discomfort, 2 = Yes, a small discomfort, 3 = Yes, a moderate discomfort, and 4 =

Metric	Response category	$\chi^2(df = 2)$	p-value
DGP	No discomfort	2.65	0.266
	Small discomfort	1.58	0.454
	Moderate discomfort	2.27	0.321
	Large discomfort	0.06	0.970
CGI	No discomfort	2.70	0.259
	Small discomfort	2.26	0.323
	Moderate discomfort	1.67	0.434
	Large discomfort	0.06	0.970
DGI	No discomfort	4.10	0.129
	Small discomfort	3.41	0.182
	Moderate discomfort	0.67	0.716
	Large discomfort	0.62	0.733
E_v	No discomfort	6.59	0.037
	Small discomfort	1.83	0.401
	Moderate discomfort	2.04	0.360
	Large discomfort	0.03	0.984
L_{mean}	No discomfort	7.82	0.020
	Small discomfort	1.53	0.465
	Moderate discomfort	0.45	0.799
	Large discomfort	0.82	0.664

Table 6.13: Results of the Kruskal-Wallis tests to assess the difference in the ranks of each of the five discomfort glare metric values between three socio-environmental groups for the four categories of glare rating scale A; a corrected significance level of $\alpha = 0.01$ is applied

Yes, a large discomfort), and an ordinal logistic regression analysis should be applied for each of the five metrics.

$$\text{Subj. assessment} \left[1|2|3|4\right] \sim \text{Metric} \begin{Bmatrix} DGP \\ CGI \\ DGI \\ E_v \\ L_{mean} \end{Bmatrix} + \text{Socio-env. context} \tag{6.1}$$

Although logistic regression analyses are nonparametric tests that usually do not require checking assumptions, there is still one assumption to verify when doing an ordinal logistic regression analysis, which is the proportional odds assumption [UCLA: Statistical

Consulting Group 2019]. This assumption establishes that the relationship between each pair of outcome groups (1|2, 2|3, 3|4) is the same.

The regression coefficients of each pair of outcome groups are therefore computed [UCLA: Statistical Consulting Group 2019]. The comparison of the coefficients is made graphically, by plotting the regression coefficients of each pair of outcome groups (the three different symbols in the plot) and observing whether these coefficients remain similar (aligned in the plot) in Figure 6.10.

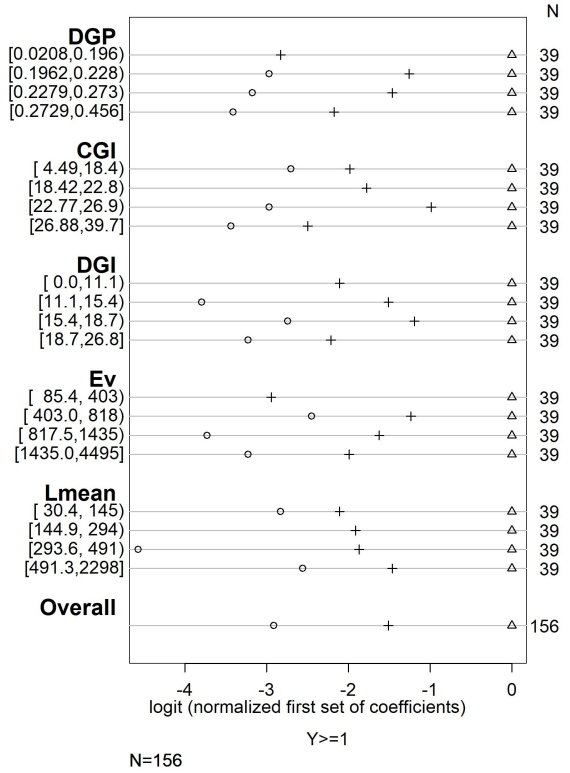


Figure 6.10: Graphical comparison of the regression coefficients of each pair of outcome groups for the proportional odds assumption that needs to be verified to apply an ordinal logistic regression

It can be observed in Figure 6.10 that the regression coefficients of each pair of outcome groups, represented by the three different symbols in the figure, are not similar as they are not horizontally aligned. The proportional odds assumption does not hold, and an ordinal logistic regression analysis can therefore not be applied.

Another possibility to perform logistic regression analyses is to transform the 4-point glare rating scale A to a binary subjective assessment, using the presence of the "No/Yes" binary classifier in the labels of the scale, as in Subsection 6.3.1. Using this binary subjective assessment, a multiple logistic regression analysis can be applied, since the model, described in Equation 6.2, contains two or more independent variables.

$$\text{Subj. assessment}\left[1|2,3,4\right] \sim \text{Metric}\begin{Bmatrix} DGP \\ CGI \\ DGI \\ E_v \\ L_{mean} \end{Bmatrix} + \text{Socio-env. context} \tag{6.2}$$

The first step of the multiple logistic regression analysis is to establish whether an interaction term should be included between the two independent variables in the model.

When two independent variables interact, the parameter of one independent variable in the logistic regression model changes depending on the value of the other independent variable [Hosmer et al. 2013]. In the case of the discomfort glare models, having an interaction term between the metrics and the socio-environmental context would mean that the relationship between the metrics and the subjective assessments differs depending on the context.

To test the need of an interaction term in the multiple logistic regression models, an LRT is applied to compare the fit of the multiple logistic regression model with the interaction term and the fit of the model without it. The results of the LRT are given in Table 6.14.

Metric	$\chi^2(df = 2)$	p-value
DGP	1.07	0.587
CGI	0.15	0.929
DGI	0.09	0.955
E_v	0.10	0.953
L_{mean}	0.80	0.671

Table 6.14: Results of the LRT to assess the need for an interaction term between the two independent variables, i.e., each of the five discomfort glare metrics and the socio-environmental context, of the multiple logistic regression models to predict the binary transformation of the ratings made on the 4-point glare rating scale A; a corrected significance level of $\alpha = 0.01$ is applied

No statistically significant differences can be observed in Table 6.14, which indicates that the data is not more likely under the model with the interaction term than under the model without it.

Since the interaction term does not seem to improve the multiple logistic regression models, the influence of the independent variables, namely the metrics and the socio-environmental context, on the dependent variable, namely the subjective assessment, can be tested separately.

As explained in Subsection 4.5.5, two tests, the Wald test and the LRT, are applied on multiple logistic regression models in this research to assess whether the independent variables influence, in a statistically significant way, the dependent variable.

For the Wald test, the socio-environmental variable, which is a categorical variable, is divided into several binary variables, as shown in Figure 4.32. The control group used for the division in the results presented in this chapter is chosen as the Swiss socio-environmental group for different reasons:

- The Swiss group has the largest number of data points.
- The subjective assessments of the Swiss group are the ones that are best predicted by the five daylight discomfort glare metrics.
- The Swiss socio-environmental context is relatively similar to European contexts, in which several daylight discomfort glare metrics have been developed, such as:

- the DGI: United Kingdom [Hopkinson 1972] and France [Chauvel et al. 1982]
- the DGI_{mod}: United Kingdom [Fisekis et al. 2003]
- the DGP: Germany and Denmark [Wienold et al. 2006]
- the E_v: Germany and Netherlands [Velds 2000]

The Wald test is first applied to look at the influence of each of the metrics and of the two binary variables opposing the socio-environmental contexts on the subjective assessments. The results of the tests are displayed in Table 6.15.

Metric	Independent variable	Estimated parameter	$\chi^2(df = 1)$	p-value
DGP	DGP	14.38	4.19	0.000***
	CH/BE	-0.61	-1.40	0.161
	CH/CL	-0.09	-0.21	0.834
CGI	CGI	0.14	4.47	0.000***
	CH/BE	-0.84	-1.92	0.055
	CH/CL	-0.36	-0.84	0.403
DGI	DGI	0.16	4.31	0.000***
	CH/BE	-0.99	-2.25	0.024
	CH/CL	-0.53	-1.21	0.227
E_v	E_v	0.00	4.10	0.000***
	CH/BE	-0.61	-1.39	0.163
	CH/CL	-0.10	-0.22	0.822
L_{mean}	L_{mean}	0.00	3.89	0.000***
	CH/BE	-0.59	-1.33	0.184
	CH/CL	0.03	0.06	0.952

Table 6.15: Results of the Wald tests to assess the statistical significance of the independent variables, i.e., each of the five discomfort glare metrics and the binary transformations of the socio-environmental context, of the multiple logistic regression models to predict the binary transformation of the ratings made on the 4-point glare rating scale A; a corrected significance level of $\alpha = 0.01$ is applied

The results of the Wald tests are similar whatever the metric used in the multiple logistic regression model. Furthermore, the Wald tests have been replicated by using the Belgian group as the control group, and the outcome of the analysis is the same.

In Table 6.15, the statistical significance of the metrics means that the parameter of that variable differs from zero. In other words, the

metrics are useful variables to predict the subjective assessments of discomfort glare from daylight made on the glare rating scale A. On the contrary, no statistically significant difference can be observed between the discomfort glare perception in the three socio-environmental contexts.

The LRT is then performed to investigate the influence of the socio-environmental context, considered as a unique variable, on the subjective assessment. The results of the tests are given in Table 6.16.

Metric	$\chi^2(df = 2)$	p-value
DGP	2.19	0.334
CGI	3.75	0.153
DGI	5.28	0.072
E_v	2.18	0.337
L_{mean}	2.38	0.305

Table 6.16: Results of the LRT to assess the statistical significance of the independent variables, i.e., each of the five discomfort glare metrics and the socio-environmental context, of the multiple logistic regression models to predict the binary transformation of the ratings made on the 4-point glare rating scale A; a corrected significance level of $\alpha = 0.01$ is applied

The results in Table 6.16 suggest that whatever the discomfort glare metric used in the model, the socio-environmental context is not a useful variable to predict the subjective assessments of discomfort glare from daylight. No statistically significant differences are observed, which indicates that the data is not more likely under the model with the socio-environmental context variable than under the model without it.

Furthermore, the logistic growth curves of the multiple logistic regression model using the binary transformation of the 4-point scale A as the dependent variable, as well as the DGP and the socio-environmental context as the independent variables, are presented in Figure 6.11. The logistic growth curves of the models using each of the five daylight discomfort glare metrics are available in Appendix G.

By a visual inspection of the logistic growth curves for the three socio-environmental contexts in Figure 6.11, a small shift can be

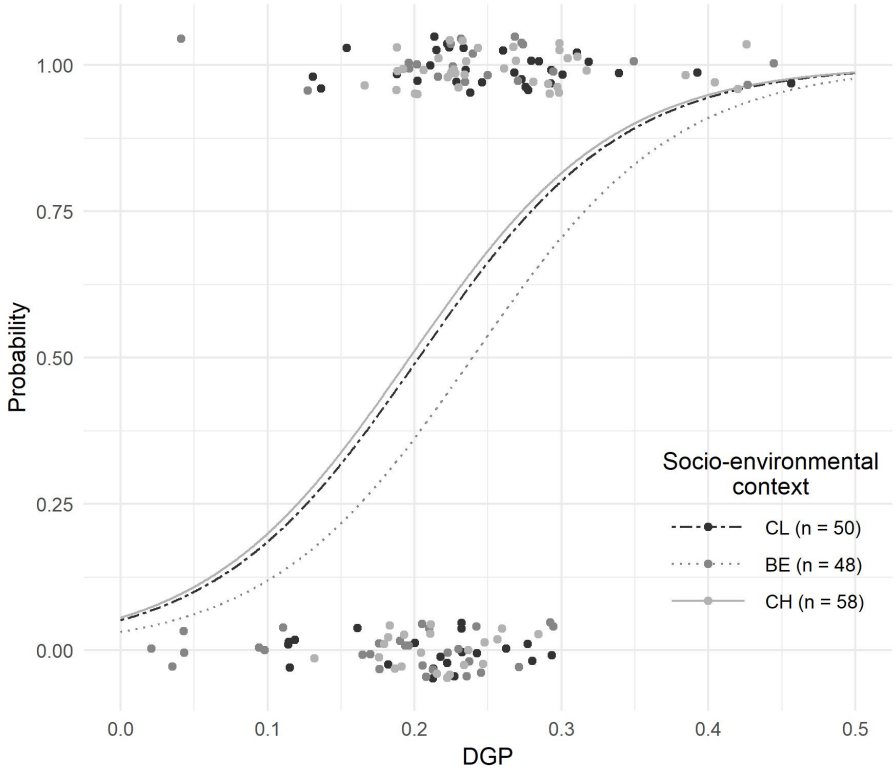


Figure 6.11: Logistic growth curve of the multiple logistic regression model based on the DGP and the socio-environmental context to predict the binary transformation of the ratings made on the 4-point glare rating scale A

observed for the Belgian curve. However, this shift was not deemed significant by either the Wald test or the LRT.

Analyses based on the OEQ

In a second step, analyses based on the subjective assessments made through the OEQ are performed to determine whether a difference in discomfort glare perception is observed when the Japanese socio-environmental context is included. In this case, the dependent variable is a binary variable, which means that not all the statistical tests from the previous subsection can be applied.

First, a Kruskal-Wallis test establishes whether the rate of binary

glare report differs between the four socio-environmental contexts. This test is relevant since a visual inspection of Figure 6.1 suggests that the lighting conditions were relatively similar in the four socio-environmental contexts. No statistically significant differences ($\chi^2(df = 3) = 3.11$, p-value$= 0.376$) are found among the four socio-environmental contexts.

Comparing the mean values of each metric for each socio-environmental context and for both the No glare report and Glare report categories would not make sense, as the mean values depend on the extreme lighting conditions and on the occurrence of those in each context.

Similarly, since the occurrence of extreme lighting conditions in each context was not controlled, applying a Kruskal-Wallis test to compare the distribution of the ranked metric values between the four contexts in both categories of the glare report could also produce confusing results. For these reasons, neither of these analyses are performed.

As the subjective assessment derived from the OEQ is a binary variable, i.e., the binary glare report ($0 =$ No glare report, $1 =$ Glare report), multiple logistic regression models can be derived as described in Equation 6.3.

$$\text{Subj. assessment}\left[0|1\right] \sim \text{Metric}\begin{Bmatrix} DGP \\ CGI \\ DGI \\ E_v \\ L_{mean} \end{Bmatrix} + \text{ Socio-env. context} \tag{6.3}$$

For the multiple logistic regression analysis, the necessity of an interaction term in the models is first assessed through an LRT. The fit of the multiple logistic regression model with the interaction term and the fit of the model without it are compared in the test. The results of the LRT are given in Table 6.17.

No statistically significant differences can be observed in Table 6.17,

Metric	$\chi^2(df = 3)$	p-value
DGP	2.20	0.531
CGI	0.39	0.941
DGI	0.43	0.934
E_v	3.18	0.365
L_{mean}	0.65	0.886

Table 6.17: Results of the LRT to assess the need for an interaction term between the two independent variables, i.e., each of the five discomfort glare metrics and the socio-environmental context, of the multiple logistic regression models to predict the binary glare report; a corrected significance level of $\alpha = 0.01$ is applied

which indicates that the data is not more likely under the model with the interaction term than under the model without it.

The influences of the independent variables, namely each of the metrics and the socio-environmental context, on the dependent variable, namely the binary glare report, are tested without an interaction term through the Wald test and the LRT.

For the Wald test, the socio-environmental variable is divided into three binary variables, and the Swiss socio-environmental group is used as the control group. The results of the Wald tests for each of the five metrics are given in Table 6.18.

The results of the Wald tests are similar whatever the metric used in the multiple logistic regression model. Furthermore, the Wald tests have been replicated by using the Belgian group as the control group, and the outcome of the analysis is the same.

In Table 6.18, the metrics are statistically significant variables, which implies that they are useful variables to predict the subjective assessments of discomfort glare from daylight made in the OEQ. On the contrary, no statistically significant difference can be observed between the discomfort glare perception in the four socio-environmental contexts.

The LRT is then performed to investigate the influence of the socio-environmental context, considered as a unique variable, on the subjective assessments. The results of the LRT are given in Table 6.19.

Metric	Independent variable	Estimated parameter	$\chi^2(df = 1)$	p-value
DGP	DGP	12.24	4.67	0.000***
	CH/BE	-0.22	-0.50	0.619
	CH/CL	-0.49	-1.16	0.244
	CH/JP	-0.27	-0.69	0.488
CGI	CGI	0.13	4.93	0.000***
	CH/BE	-0.40	-0.91	0.365
	CH/CL	-0.70	-1.62	0.106
	CH/JP	-0.52	-1.34	0.181
DGI	DGI	0.14	4.52	0.000***
	CH/BE	-0.55	-1.26	0.208
	CH/CL	-0.81	-1.89	0.059
	CH/JP	-0.62	-1.62	0.106
E_v	E_v	0.00	4.46	0.000***
	CH/BE	-0.26	-0.60	0.545
	CH/CL	-0.50	-1.19	0.236
	CH/JP	-0.37	-0.96	0.339
L_{mean}	L_{mean}	0.00	4.47	0.000***
	CH/BE	-0.27	-0.61	0.545
	CH/CL	-0.34	-0.79	0.430
	CH/JP	-0.28	-0.71	0.476

Table 6.18: Results of the Wald tests to assess the statistical significance of the independent variables, i.e., each of the five discomfort glare metrics and the binary transformations of the socio-environmental context, of the multiple logistic regression models to predict the binary glare report; a corrected significance level of $\alpha = 0.01$ is applied

Metric	$\chi^2(df = 3)$	p-value
DGP	1.40	0.707
CGI	3.03	0.388
DGI	4.30	0.231
E_v	1.62	0.656
L_{mean}	0.80	0.851

Table 6.19: Results of the LRT to assess the statistical significance of the independent variables, i.e., each of the five discomfort glare metrics and the socio-environmental context, of the multiple logistic regression models to predict the binary glare report; a corrected significance level of $\alpha = 0.01$ is applied

The results in Table 6.19 suggest that whatever the discomfort glare metric used in the model, the socio-environmental context is not statistically significant, hence is not useful to predict the subjective assessments of discomfort glare from daylight made in the OEQ.

Furthermore, the logistic growth curves of the multiple logistic regression model using the binary glare report as the dependent variable, as well as the DGP and the socio-environmental context as the independent variables, are presented in Figure 6.12. The logistic growth curves of the models using each of the five daylight discomfort glare metrics are available in Appendix G.

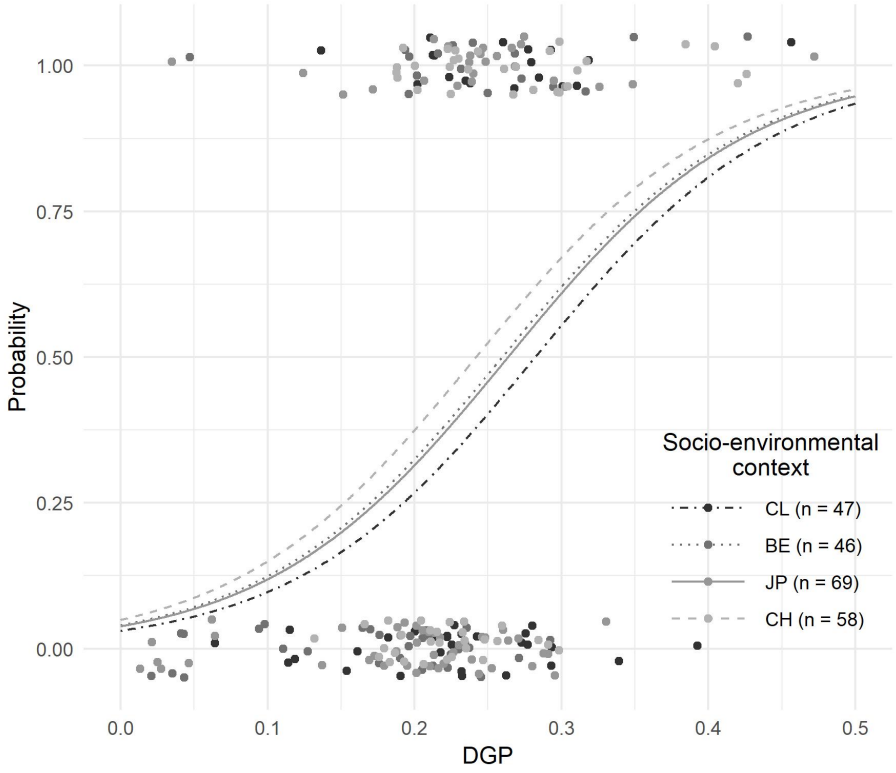


Figure 6.12: Logistic growth curve of the multiple logistic regression model based on the DGP and the socio-environmental context to predict the binary glare report

The logistic growth curves of the four socio-environmental contexts in Figure 6.12 are very close, but the Swiss and Chilean curves

are still slightly shifted. These shifts seem to be, however, not statistically significant according to either the Wald test or LRT.

6.6.2 Discussion

To determine whether there is a difference in discomfort glare perception, and more specifically in the sensitivity to discomfort glare, from daylight between subjects from different socio-environmental contexts, the statistical analyses are conducted in two parts: one part of the analysis is based on the subjective assessments made through the 4-point glare scale A, and the other part is based on the subjective assessments made through the OEQ. The results are similar in both parts; hence the discussion is common.

Firstly, the visual inspection of the mean metric values of each context for each category of the 4-point glare rating scale A does not show any consistent trend across the glare categories and across the metrics. This observation is confirmed by the results of the Kruskal-Wallis tests, as no statistically significant differences can be observed between the socio-environmental contexts. In these first results, there is no strong and/or consistent evidence that supports the hypothesis that discomfort glare perception differs between the four socio-environmental contexts. However, the results should be interpreted with extra care as several groups have a very small number of data points, questioning the reliability of their results.

Secondly, the subjective assessments are analyzed in the form of binary variables, either with the binary transformation of the 4-point glare rating scale A or with the binary glare report. In this way, the uncertainty related to small numbers of data points in some groups are avoided, and multiple logistic regression analyses can be performed. There are no evidence of a statistically significant difference between the socio-environmental contexts from the results of the Wald tests and LRT, whatever the subjective assessment method and the daylight discomfort glare metric used in the logistic regression model.

Some offsets can be observed between the logistic growth curves in Figures 6.11 and 6.12. However, these offsets seem not statisti-

cally significant according to the results of the Wald tests and LRT. Furthermore, they are not consistent when different subjective assessment methods are used. For instance, the curve of the Belgian socio-environmental group based on the binary transformation of the 4-point scale A is slightly shifted on the right compared to that of the Chilean group (Figure 6.11), whereas the curve based on the binary glare report is slightly shifted on the left compared to that of the Chilean group (Figure 6.12). For these reasons, it is hypothesized that the offsets between the curves might be due to some noise or experimental bias in the data.

In all the results presented in this section, there seems to be no evidence that supports the hypothesis that discomfort glare perception from daylight, and more specifically the sensitivity to discomfort glare, differs between subjects from different socio-environmental contexts. Nonetheless, more research is required to confirm these results.

Furthermore, it could be hypothesized that the difference in discomfort glare perception between different socio-environmental contexts, which has been either observed or suggested in the literature [Ichikawa et al. 1964; Subova et al. 1991; Iwata et al. 1992a; Pulpitlova et al. 1993; Lee et al. 2007b; Huang et al. 2016; Ko et al. 2017; Mangkuto et al. 2017], might be due to differences in the protocol between the studies used in the comparison, as first suggested by Iwata et al. [Iwata et al. 1992a].

In the literature, there are eight studies in which the hypothesis that subjects from different socio-environmental contexts have different discomfort glare perceptions is supported. In seven of these eight studies, this hypothesis is deduced based on the comparison of discomfort glare perception results obtained from the data of the study to published discomfort glare perception results from a former study. At the very least, the investigator(s) and equipment are not the same between the two studies of the comparison; at worst, the entire protocol differs between the two studies.

In the last study supporting the hypothesis, the comparison between the sensitivity to discomfort glare of two different socio-envi-

ronmental groups was made on the basis of data from a single study. The data from both groups were thus collected with the same investigator(s) and equipment, and according to the same protocol. However, one socio-environmental group in the study was composed of 168 Koreans and the second was composed of eight Caucasians.

The data used for the comparison in this study constitute four balanced socio-environmental groups, each of which is composed of at least 30 subjects, and were collected with the same investigator and equipment, as well as the same protocol. This data did not lead to robust evidence supporting the findings of the previous studies that suggested a difference in discomfort glare perception based on socio-environmental context.

Furthermore, two recent studies, which were also specifically designed to study some influence of the socio-environmental context on visual perceptions, support these results. Firstly, a laboratory study in Japan could not observe any differences in discomfort glare perception from daylight between Middle Eastern and Japanese subjects, although it is not said for how long the Middle Eastern subjects had been living in the Japanese socio-environmental context and whether they had acclimatized to it [Iwata 2018]. Secondly, from another laboratory study using virtual reality, no differences in subjective visual perception of architectural spaces could be detected between 138 subjects from the Greek socio-environmental context and 120 subjects from the Swiss context [Chamilothori 2019].

Finally, the five daylight discomfort glare metrics are found to be statistically significant variables of the multiple logistic regression models. This result implies that the metrics can be used to predict the subjective assessments of discomfort glare made by the subjects.

6.7 Conclusion

In this chapter, the influence of the socio-environmental context on discomfort glare perception from daylight was investigated. For this purpose, data, i.e., two types of subjective assessment of discomfort glare and five daylight discomfort glare metrics, collected in four different socio-environmental contexts, was analyzed.

The subjective assessments of discomfort glare consisted of an evaluation made by the subject on the 4-point glare rating scale A, as well as a binary glare report derived from the subjects' answer to an OEQ. The five daylight discomfort glare metrics were selected in order to be simple, well known in the field, representative of the three types of discomfort glare metrics, and the most performant and robust of their type [Wienold et al. 2019]. They include the DGP, CGI, DGI, E_v, and L_{mean}.

The datasets collected in the four socio-environmental contexts were assumed to be comparable. Apart from three variables, the distributions of baseline characteristics and discomfort glare stimuli appeared visually similar between the four contexts. From the three variables not evenly distributed, it was hypothesized that only the unequal distribution of the view through the window was due to a sampling issue. There is evidence in the literature suggesting that the unequal distributions of the subjects' iris pigmentation and chronotype are representative of an imbalance of these variables in the population.

Nevertheless, these three variables could influence discomfort glare perception. Their relationship with subjects' subjective assessments of discomfort glare will be investigated in depth in the following chapter, in order to avoid a potential confounding effect on the influence of the socio-environmental context.

After evaluating to what extent the daylight discomfort glare metrics could predict discomfort glare perception in each socio-environmental context, the results showed that the robustness of the prediction of the metrics varied depending on the subjective assessment method used in two socio-environmental contexts.

Additional analyses led to the hypothesis that the subjective assessments made via the glare rating scales (A, B, and C) in the Japanese context and those made via the OEQ in the Chilean context were biased. Further studies are required to confirm the hypotheses that have been made in this regard. Nonetheless, the subjective assessments that could not be predicted by the glare metrics were removed from the datasets, since the following analyses are based on these metrics to ensure a fair basis of comparison.

The two issues encountered in this chapter (Sections 6.4 and 6.5) raise, however, two relevant questions regarding discomfort glare studies nowadays:

1. What method(s) should be used to collect the least biased subjective assessments of discomfort glare?
2. Since the indoor environment is a multi-sensory environment, should it not be studied as a whole so that interactions between environmental factors are included?

Regarding the first question, a few insights will be given in Section 8.2 as a deeper investigation of the subjective assessment methods used in this study will be carried out.

Regarding the second question, a small part of it will be addressed in Section 7.4 as the interaction between daylight discomfort glare and thermal factors will be investigated.

These two questions are fundamental to produce relevant knowledge in the field of discomfort glare perception, and more generally of comfort in indoor environments. In the future, it is highly recommended that dedicated studies try to answer them.

The results in this chapter suggest that the five daylight discomfort glare metrics are reasonable models to evaluate discomfort glare perception from daylight in the four studied socio-environmental contexts. Moreover, no consistent and/or strong evidence of a difference in the sensitivity to discomfort glare from daylight between subjects from the four contexts could be found. This last result was not expected in view of the existing literature on the topic.

It should be noted that the lack of evidence of different discomfort glare perceptions in the different socio-environmental contexts is in disagreement with previously published results from the same author [Pierson et al. 2017]. The disagreement is assumed to be related to the different glare source detection methods applied between the two studies. In the earlier study [Pierson et al. 2017], the factor method with a factor 7 (Subsection 4.2.6) was used as the glare source detection method. However, it was observed that this factor method produced unreliable glare source detections, and thus unreliable discomfort glare metric evaluations, especially for very dim or very bright visual scenes [Pierson et al. 2018a]. Since the Chilean dataset used in the earlier study contained more extreme visual scenes, whether dim or bright, than the Belgian dataset (SD_{Ev} = 2494 lux for the Chilean dataset, and SD_{Ev} = 594 lux for the Belgian dataset), it is assumed that the discomfort glare metric values calculated for this dataset were distorted and led to unreliable results.

Furthermore, the three types of discomfort glare metrics, i.e., saturation-based, contrast-based, and metrics including both effects, were used in the statistical analyses. Their respective performance can be studied in the framework of this study. Unsurprisingly, the metrics including the saturation effect in their model can be observed as being slightly better performing in this study. The selection rules for the studied visual scenes indeed aimed at increasing the probability of saturation glare against that of contrast glare. The performance of these metrics was deemed a bit better than that of contrast-based metrics from the analyses, as they offer smaller gaps in the correlation coefficients and AUC values between the contexts, as well as slightly higher correlation coefficients and AUC values.

To conclude, the main research question of this study asked whether the socio-environmental context of a subject influence her/his discomfort glare perception from daylight in office buildings. For this purpose, the hypothesis that needed to be verified was that subjects from at least one of the four socio-environmental contexts, i.e., Japan, Chile, Belgium, and Switzerland, have a different sensi-

tivity to discomfort glare from daylight than subjects from another one of the four contexts. In this chapter, the analyses of the data collected in office buildings in the four contexts could not demonstrate any statistically significant differences in the sensitivity to discomfort glare from daylight between the subjects from the different contexts. This result can be visually recognized from the logistic growth curves of each context in Figures 6.11 and 6.12.

Chapter 7

Results: First Additional Research Question

7.1 Introduction

In the previous chapter, the collected data was analyzed to study the influence of the socio-environmental context on discomfort glare perception from daylight, which answers the main research question of the study. No statistically significant differences in the sensitivity to discomfort glare could be observed between the subjects from the four socio-environmental contexts. The results show therefore no evidence of an influence of the socio-environmental context on discomfort glare perception from daylight in office buildings.

Besides the socio-environmental context, 13 additional factors have been preselected from the 31 originally listed in the state of the art, to be further investigated in this research. These 13 factors are the focus of the first additional research question of the study, which aims at determining whether some of them have a probable influence on the subject's discomfort glare perception from daylight in office buildings.

In contrast to the main research question for which the hypothesis that the socio-environmental context influences discomfort glare perception was tested, no specific predictions regarding the influence of those 13 factors were made prior to the analyses. Moreover, the protocol of the study was not developed specifically to test these factors. The purpose of the first additional research question is to analyze the data regarding these additional factors and suggest which of them might have higher probabilities of influencing discomfort glare perception from daylight thereby identifying promising topics for future research.

Furthermore, a qualitative analysis of the Chilean subjects' answers to the OEQ in the previous chapter led to the hypothesis that these subjects strongly associated daylight with thermal discomfort (most probably due to overheating). As already argued in the literature [Torresin et al. 2018], indoor environments are multi-sensory environments, and interactions between different indoor environmental factors, i.e., visual and thermal factors in this case, are to be expected. Although further dedicated research should be conducted to investigate these multiple potential interactions, a small part of

this task is tackled in this chapter (Section 7.4), as the interaction between daylight discomfort glare and thermal factors is investigated.

For the results presented in this chapter, the statistical tests are completed with the software R version 3.5.2 [R Core Team 2018], as well as:

- the R package *stats* version 3.5.2 [R Core Team 2018] for the fitting of logistic regression models, some of the LRT, the Spearman's rank correlations, the Wilcoxon rank sum tests, and the Fisher's exact tests;
- the R package *GGally* version 1.4.0 [Schloerke et al. 2018] for the pairwise correlation matrix;
- the R package *car* version 3.0-2 [Fox et al. 2019] for the Variance Inflation Factor (VIF) analysis, and some of the LRT.

7.2 Selection of Additional Factors to Study

Besides the socio-environmental context of the subject and the experimental biases, 13 additional factors related to the subject or to the context and potentially influencing discomfort glare perception from daylight are aimed to be investigated in the scope of this study.

These factors are gender, age, chronotype, glare sensitivity (through the self-assessed glare sensitivity), visual acuity (through the optical correction), iris pigmentation, physical state, emotional state, fatigue, caffeine ingestion, attractiveness of the view through the window, air temperature, and the time of day.

The purpose of this chapter is to investigate which of these 13 factors have a higher probability of influencing discomfort glare perception from daylight by analyzing the collected data.

For this purpose, the principal statistical analysis that is applied is a multiple logistic regression model. As this analysis only requires a binary variable as dependent variable, the final dataset displayed in Table 4.8 for analyses based on the subjective assessment made via the OEQ is used.

In this dataset, the data points corresponding to subjects who had been living in one of the four contexts for less than two years are included, and the data points of the subjects of the four contexts are mixed, since the socio-environmental context appears not to influence discomfort glare perception.

The analyses conducted in Chapter 6 led to the hypothesis that some of the subjective assessments made through the OEQ in the Chilean context might be biased due to an association between daylight and thermal comfort. Since these subjective assessments are ambiguous and there is no way to know in retrospect what the subject meant by her/his answer to the OEQ, it is decided not to include that data in the analyses in this chapter.

Besides the 4 ambiguous Chilean data points, 9 outliers (1 in Chile and 8 in Switzerland) have been removed from the dataset due to

their high vertical illuminance value ($E_v > 6000$ lux). A visual inspection of the visual scenes of these nine date points show that the sun was present in the FOV of each scene, increasing the risk to cause disability glare.

In conclusion, the dataset that will be used for the analysis of the influence of the 13 additional factors on discomfort glare perception from daylight is described in Table 7.1.

Dataset	N	Binary glare report	
		No	Yes
Total	250	150	100

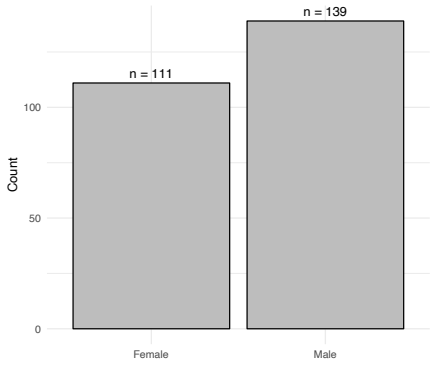
Table 7.1: Information on the dataset (E_v outliers and ambiguous data points removed) used for the selection of additional factors to study (Section 7.2) and for the analysis of the influence of additional factors on discomfort glare perception (Section 7.3)

Since all the tests looking at additional influencing factors are still performed considering the five daylight discomfort glare metrics, the Bonferroni correction remains, and the significance level applied in this chapter is $\alpha = 0.01$ ($\alpha < 0.01^{*}$ for statistical significance; $\alpha < 0.002^{**}$ for statistical high significance; and $\alpha < 0.0002^{***}$ for statistical very high significance).

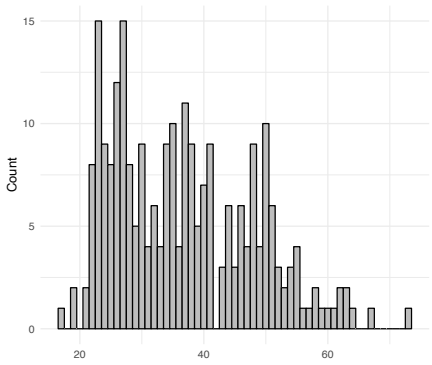
7.2.1 Graphical Analysis

In order to assess through statistical analyses which additional factors have a high probability of influencing discomfort glare perception from daylight, the distributions of the 13 factors are investigated for uniformity across their categories or along their scale. Since these variables were not controlled in the study design, the proportion of data points between categories or areas of a scale might be very unbalanced, which might distort the results.

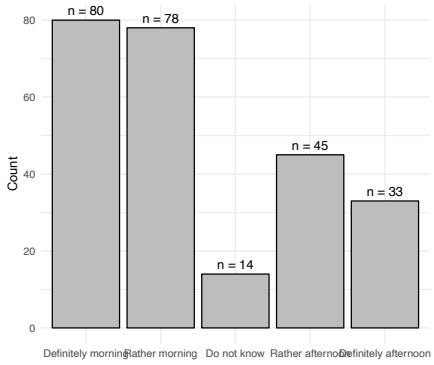
The distributions of the data regarding the 13 factors are graphically displayed in Figure 7.1.



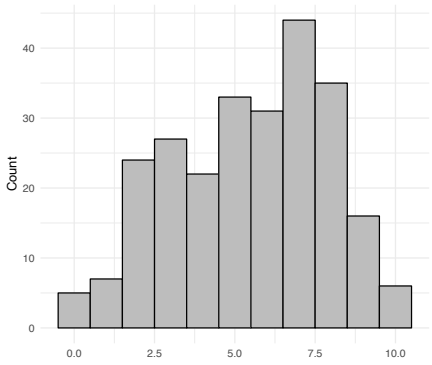
(a) Gender of the subject



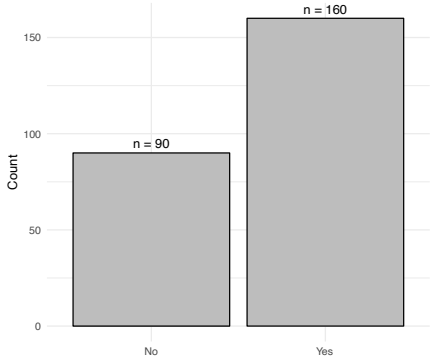
(b) Age of the subject



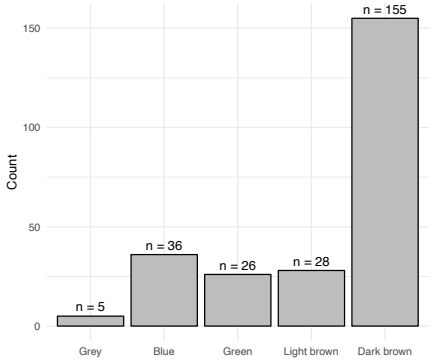
(c) Chronotype of the subject



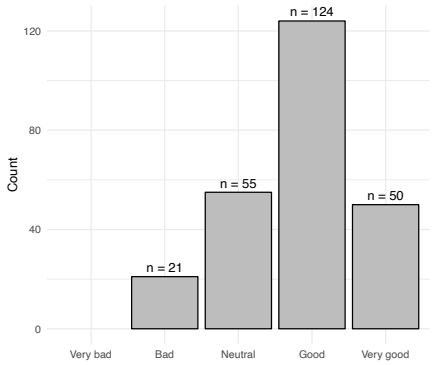
(d) Self-assessed glare sensitivity



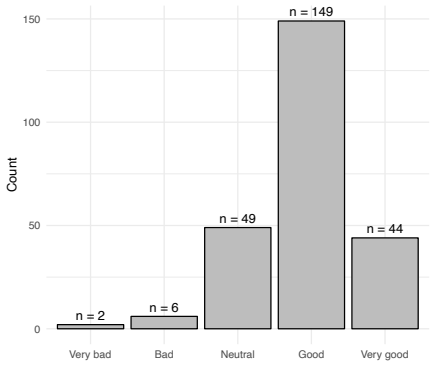
(e) Optical correction of the subject



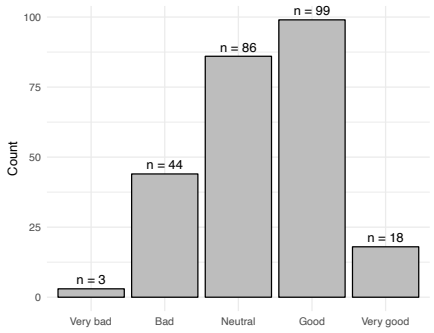
(f) Iris pigmentation of the subject



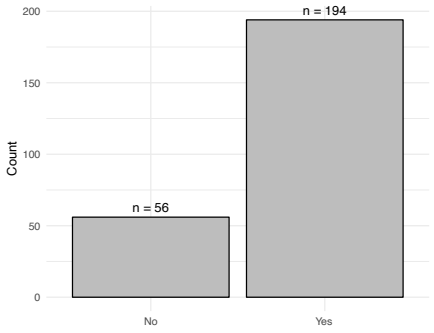
(g) Physical state of the subject



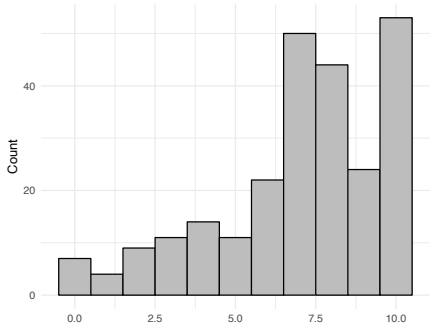
(h) Emotional state of the subject



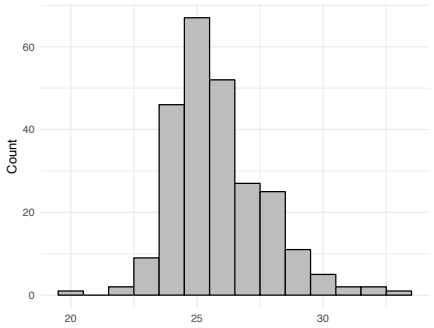
(i) Fatigue of the subject



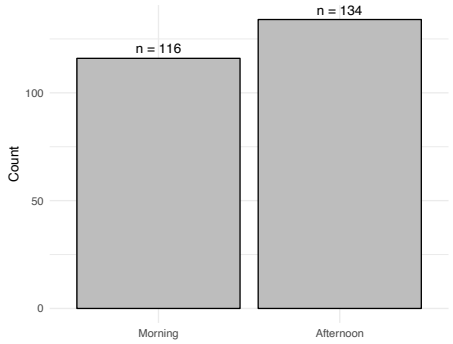
(j) Caffeine ingestion of the subject



(k) Attractiveness of the view ...



(l) Air temperature of the room



(m) Time of the day

Figure 7.1: Bar plots representing the distribution of the data for the 13 additional factors potentially influencing discomfort glare perception

A visual inspection of the graphs in Figure 7.1 shows that, regarding the categorical factors, two of them are properly balanced, i.e., the gender and the time of day. Conversely, large imbalances can be observed for iris pigmentation and caffeine ingestion, and smaller imbalances for chronotype and optical correction. Regarding the ordinal and continuous factors, the visual inspection indicates that most of the factors have a somehow skewed distribution.

Since large imbalances cause a reduction in statistical power [Ciolino et al. 2011], the largest imbalances should be reduced when possible.

For this purpose, it is decided to investigate the iris pigmentation as a binary variable, with the Light color-eyed subjects, on the one hand, including the grey, blue, green, and light brown eyes, and the Dark-color-eyed subjects on the other hand, including the dark brown eyes. By regrouping the light color groups of the iris pigmentation variable, the imbalance is reduced (Figure 7.2).

As there is no possibility of reducing the imbalance regarding caffeine ingestion, and subsampling the data is not recommended in view of the rather small dataset, further results concerning this factor should be interpreted carefully.

In summary, the distributions of all the factors, except for caffeine ingestion, are not uniform, but do not show very large imbalances.

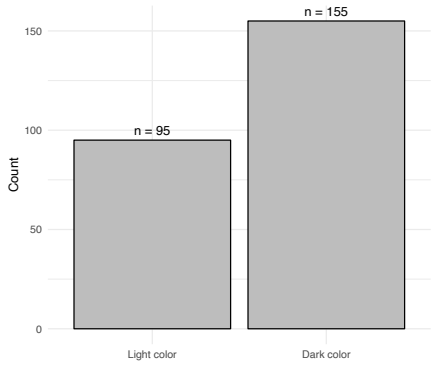


Figure 7.2: Bar plot representing the distribution of the data for the iris pigmentation of the subject, of which the categories have been grouped

Furthermore, in a study on the predictive capability of logistic regression models, it was demonstrated that it is better to use a sample that has the same class distribution as the original population rather than ensuring that the classes are balanced. Since the dataset was randomly collected in four countries, it is expected that its distribution is somehow representative of the population working in daylit offices in these countries. Therefore, it is assumed that the potential influence of 12 factors on discomfort glare perception from daylight can be investigated through a multiple logistic regression analysis.

7.2.2 Subsetting of the Factors

In regard to the dataset size, testing 12 factors (caffeine ingestion removed), besides the socio-environmental context, might produce misleading results since the risk of getting a Type I error is high. As in Section 5.4, there are two solutions to help ensure that none of the 12 factors are detected as significantly influencing discomfort glare perception only due to chance: a stricter Bonferroni correction applied to the significance level or a reduction in the number of tests by cutting out some of the factors.

As the significance level is already relatively strict, with $\alpha = 0.01$, correcting it again would also significantly reduce the power of de-

tecting a true effect. Therefore, the number of factors to study must be reduced.

A common rule of thumb in the literature to determine how many variables can be inserted in a logistic regression model is the ten Events per Predictor Variable (EPV) rule [Ranganathan et al. 2017]. According to this rule, which is sometimes seen as too conservative [Vittinghoff et al. 2007], there should be at least ten outcome events per independent variable.

Since the dependent variable of the model is the binary glare report, the smallest group of outcome events is the Glare report one, with 100 events. By dividing this number by ten, it means that ten independent variables, namely ten factors, can be inserted in the multiple logistic regression model.

However, it should be taken into account that if a categorical variable having k categories is inserted in the model, this variable is divided into $k - 1$ binary variables in the model, as explained in Subsection 4.5.5. Therefore, it might be useful to combine some categories of a categorical variable inserted in the model if the combination is meaningful.

The five daylight discomfort glare metrics have to count for one of the 10 independent variables, as these are systematically included in the model. Moreover, the socio-environmental context has already been investigated with this data, and should also count as three of the 10 variables due to the four socio-environmental categories. The influence of six out of the 12 additional factors can therefore be tested through a multiple logistic regression analysis.

First, three factors were highlighted as potential confounding variables in Section 6.2, since their distributions were not similar for the four socio-environmental contexts. These factors, namely the iris pigmentation of the subject, the chronotype of the subject, and the attractiveness of the view through the window, have to be tested to ensure that their potential influence on discomfort glare perception does not have a confounding effect with the socio-environmental context. This can be done by inserting these three factors alongside the socio-environmental context in a multiple logistic regression

model, and looking for the change in odds ratio of the socio-environmental context when each of these three factors is removed from the model [Pourhoseingholi et al. 2012].

The number of binary independent variables required for the chronotype variable can be reduced to two by combining the Definitely morning and Rather morning groups, as well as the Rather afternoon and Definitely afternoon (Figure 7.3). Moreover, the iris pigmentation variable is a binary variable as a result of the light color eyes grouping, counting as one independent variable. Lastly, the attractiveness of the view through the window also counts as a unique independent variable as it is continuous.

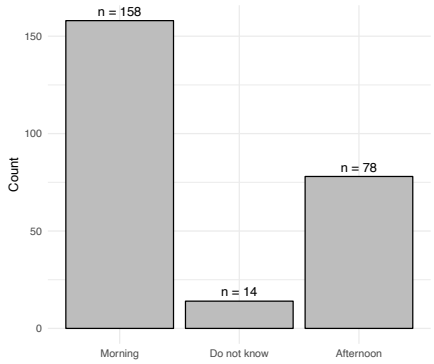


Figure 7.3: Bar plot representing the distribution of the data for the chronotype of the subject, of which the categories have been grouped

Moreover, in Section 6.5, an interaction between thermal factors and daylight discomfort glare is suggested by a qualitative analysis of the data. Although the interaction will be investigated more thoroughly in Section 7.4, this hypothesis suggests that the air temperature of the room is a factor influencing discomfort glare perception from daylight. This continuous factor is therefore the ninth independent variable selected for the analysis.

One last independent variable can be selected among the remaining factors. However, this variable cannot be a categorical variable with more than two categories, which excludes the physical state, the emotional state, and the fatigue of the subject.

In the remaining factors, two of them have their influence classified as Almost certainly null by the influence indicator [Pierson et al. 2018b]. The gender and the optical correction of the subject are therefore excluded.

Furthermore, the time of the day has only been studied by two different research groups (three studies come from the same research group). Its potential influence on discomfort glare perception is therefore not strongly supported in the literature, and it is decided to exclude it as well.

The age and the self-assessed glare sensitivity of the subject are both suitable to be selected for the analysis. Since only one last independent variable can be inserted in the multiple logistic regression model, the age factor is excluded. The literature shows that if there is an effect of age, this effect is observable between young ($< 25 - 35$ years old) and elderly ($> 50 - 60$ years old) subjects [Facchin et al. 2017; Iwata et al. 1997; Wolska et al. 2014]. In this dataset, 85 subjects (34%) are less than 30 years old, but only 14 subjects (5.6%) are over 60 years old. It is assumed that the number of elderly subjects in the dataset is not sufficient to observe any effect of age on discomfort glare perception from daylight. The self-assessed glare sensitivity of the subject, which is more uniformly distributed in the dataset as seen in Figure 7.1d, is the last independent variable to be selected for the analysis.

In conclusion, the five factors related to the subject and to the context that are included in the multiple logistic regression model in order to determine which of them has/ve a probable influence on subjects' discomfort glare perception from daylight, are:

- chronotype of the subject
- self-assessed glare sensitivity of the subject
- iris pigmentation of the subject
- attractiveness of the view through the window
- air temperature of the room

7.3 Influence of Additional Factors

In this section, a multiple logistic regression analysis is performed to determine whether one of the five variables selected previously can improve the evaluation of discomfort glare perception from daylight more than expected by chance [McDonald 2014].

Before performing this analysis, the three additional factors that were detected as not evenly distributed between the four socio-environmental contexts by a visual inspection (Section 6.2) have to be tested in order to define whether they are potentially confounding the socio-environmental context.

If this is the case, the influence of the socio-environmental context should be tested again by including the confounding variables in the multiple logistic regression model. By adjusting for confounding variables, hence including them in the model, the effect of the socio-environmental context on discomfort glare perception can be investigated while controlling, namely keeping constant, these other variables.

Moreover, when performing a multiple logistic regression analysis with a large number of variables, these variables need to be checked for collinearity, namely linear relationships that might exist between two or several of them. Collinearity is problematic in logistic regressions, and causes unreasonable parameter estimates or parameter estimates changing erratically in response to small changes in the model or in the data [Hosmer et al. 2013].

The dataset used for the following analyses is the same as the one presented in Table 7.1.

7.3.1 Analyses and Results

Tests for Confounding Variables

To determine that a covariate is confounding a specific predictor, a common rule of thumb establishes that the amount of adjustment of the parameter of the predictor brought by the covariate must be higher than 20% [Hosmer et al. 2013]. The amount of adjustment

is a percentage of the adjusted log-odds ratio calculated according to Equation 7.1.

$$\Delta\beta = 100 \cdot \frac{(\theta_1 - \beta_1)}{\beta_1} \tag{7.1}$$

where:

$\Delta\beta$ is the amount of adjustment [%]

θ_1 is the parameter estimate of the predictor of interest in the logistic regression model excluding the covariate

β_1 is the parameter estimate of the predictor of interest in the logistic regression model including the covariate

The amount of adjustment of the three parameters of the binary variables derived from the socio-environmental context variable is evaluated for each of the three potential confounding variables, namely chronotype, iris pigmentation, and the attractiveness of the view through the window, and for each of the five daylight discomfort glare metrics (Table 7.2). In Table 7.2, the Swiss group is used as the control group to derive the binary variables from the socio-environmental context factor. However, these analyses have been replicated by using the Belgian group as the control group, and the outcome of the analysis is the same.

The amount of adjustment of the estimated parameters for the socio-environmental context (Table 7.2) seems to indicate that the three variables might be confounding variables, and especially the chronotype of the subject. The percentage of adjustment of the estimated parameters for the socio-environmental context largely depends on the metric on which the model is based, but often exceeds the 20% adjustment threshold.

Therefore, the relationship between the socio-environmental context of the subjects and their subjective assessments of discomfort glare from daylight should be assessed a second time, by including the confounding variables together with the socio-environmental context variable in a multiple logistic regression model. This will be done later in this section.

Metric	Covariate	Amount of adjustment: $\Delta\beta$ [%]		
		CH/CL	CH/BE	CH/JP
DGP	Chronotype of the subject	39	99	1
CGI		109	254	130
DGI		151	365	185
E_v		35	120	44
L_{mean}		-31	78	-12
DGP	Iris pigmentation of the subject	-11	5	-37
CGI		-11	2	-25
DGI		-9	2	-21
E_v		-9	3	-22
L_{mean}		-24	4	-43
DGP	Attractiveness of the view through the window	54	13	-52
CGI		15	-2	-32
DGI		13	-5	-27
E_v		60	-5	-42
L_{mean}		681	3	-52

Table 7.2: Amounts of adjustment of the parameters of the socio-environmental context binary variables when each of the three potential confounding variables is added in the multiple logistic regression model based on each of the five discomfort glare metrics

Tests for Collinearity

A first method to check for collinearity between the covariates is to look graphically for pairwise correlations among these covariates through the correlation matrix (Figure 7.4). By visually inspecting Figure 7.4, no strong correlations between the covariates can be detected.

An additional test, the Variance Inflation Factor (VIF) analysis, is applied to check for collinearity in the model. The VIF is the ratio of variance in a model with multiple covariates, divided by the variance of a model with only one independent variable [James et al. 2013]. This indicator quantifies the severity of collinearity by evaluating how much the variance of a parameter estimate is increased because of collinearity.

In general, a VIF exceeding 10 is regarded as an indicator of collinearity [Field et al. 2012]. In weaker models such as a logistic regression, a VIF of 2.5 might already be a cause of concern regarding collinearity [Midi et al. 2013].

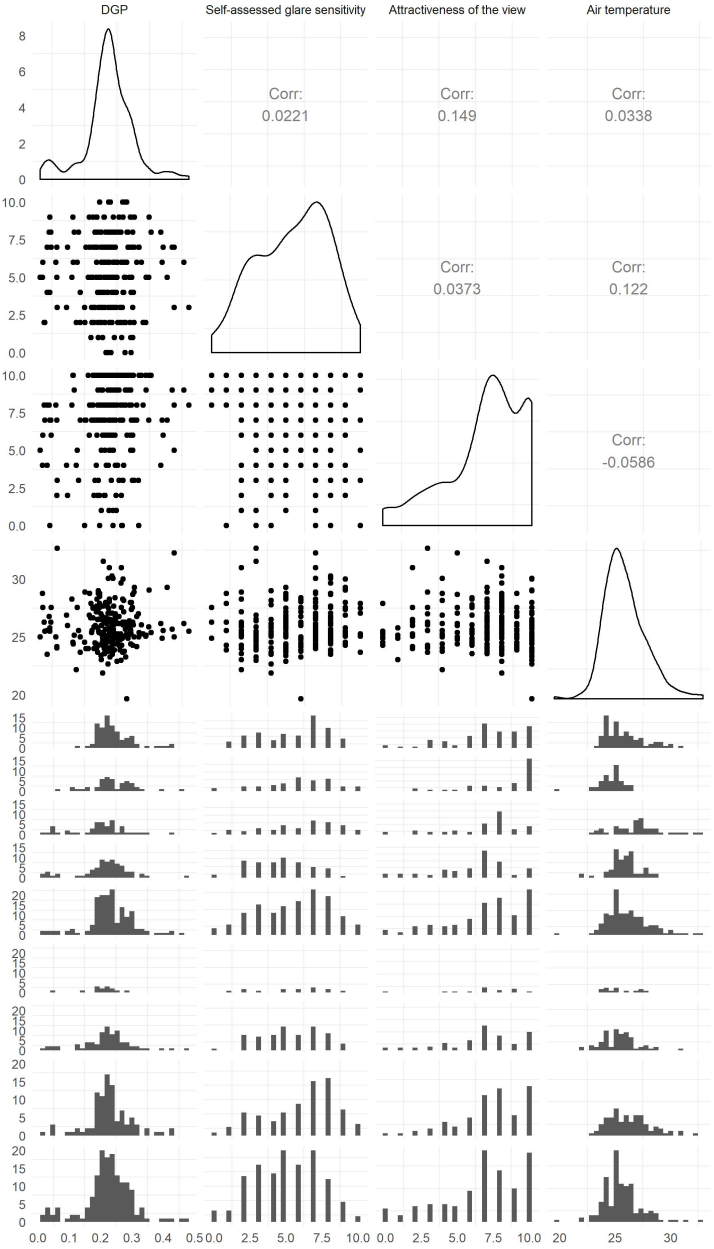
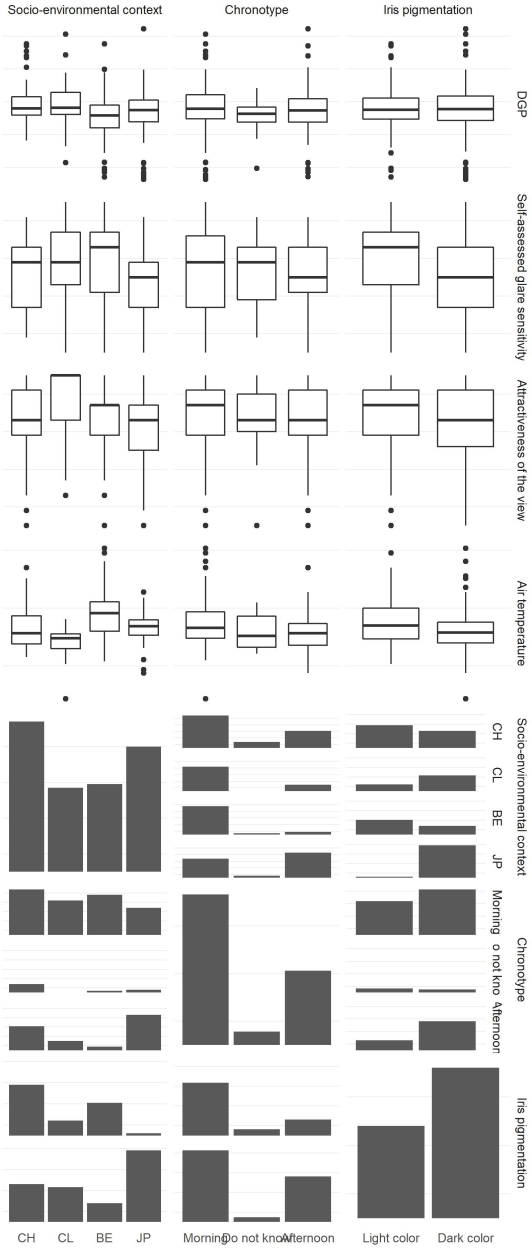


Figure 7.4: Pairwise correlation matrix giving an overview of the relationships between each



of the covariates of the multiple logistic regression model

Due to the presence of categorical variables, the Generalized Variance Inflation Factor (GVIF), instead of the VIF, is evaluated for each covariate of the five multiple logistic regression models based on the five daylight discomfort glare metrics. The Generalized Variance Inflation Factor (GVIF) values are given in Table 7.3.

	GVIF						
Metric	Metric	Socio-environmental context	Chronotype	Self-assessed glare sensitivity	Iris pigmentation	Attractiveness of the view	Air temperature
DGP	1.11	2.21	1.31	1.13	1.37	1.18	1.28
CGI	1.12	2.28	1.32	1.14	1.42	1.14	1.27
DGI	1.14	2.32	1.33	1.14	1.42	1.13	1.28
E_v	1.13	2.24	1.29	1.12	1.37	1.18	1.30
L_{mean}	1.13	2.28	1.28	1.12	1.37	1.18	1.30

Table 7.3: GVIF for the covariates of the multiple logistic regression models based on each of the five discomfort glare metrics to detect collinearity

Since all the Generalized Variance Inflation Factor (GVIF) values are below the threshold of 2.5, it is assumed that there is no problems of collinearity between the covariates of the multiple logistic regression model.

Tests for Influence

In order to answer the second additional research question and determine whether some of the five factors selected in Section 7.2 have a probable influence on the subject's discomfort glare perception from daylight in office buildings, the influence of these factors is tested through a multiple logistic regression analysis.

A multiple logistic regression model is derived, as described in Equation 7.2, with the binary glare report derived from the OEQ as the dependent variable, and each of the five daylight discomfort glare metrics and the potentially influencing factors selected as the independent variables.

$$\begin{aligned}\text{Subj. assessment } \left[0|1\right] \sim \text{Metric} \begin{Bmatrix} DGP \\ CGI \\ DGI \\ E_v \\ L_{mean} \end{Bmatrix} \\ + \text{ Socio-environmental context} \\ + \text{ Chronotype} \\ + \text{ Self-assessed glare sensitivity} \\ + \text{ Iris pigmentation} \\ + \text{ Attractiveness of the view} \\ + \text{ Air temperature of the room}\end{aligned} \tag{7.2}$$

An LRT is conducted for each independent variable of the model and for the five daylight discomfort glare metrics, to assess the influence of the additional factors on the binary glare report from the subjects. The results of the tests are shown in Table 7.4. The Swiss group is once again used as the control group in the results presented, but these results were similar when reproduced with the Belgian group used as the control group.

Besides the daylight discomfort glare metrics, two independent variables, namely the self-assessed glare sensitivity of the subject and the attractiveness of the view through the window, are statistically significant in predicting the binary glare report of the subjects. This result holds for the models based on each of the five metrics.

Furthermore, the interactions between each of the five metrics and the two variables need to be tested.

If there is an interaction between one of the two variables and the metrics, it would mean that the relationship between the metrics and the subjective assessments differs depending on that variable. The need for an interaction term in the model is tested through an LRT, which determines whether the fit of the model is better with the interaction term than without it.

Metric	Independent variable	χ^2	*df*	*p*-value
DGP	DGP	41.30	1	0.000***
	Socio-environmental context	1.68	3	0.642
	Chronotype	2.96	2	0.228
	Self-assessed glare sensitivity	8.58	1	0.003*
	Iris pigmentation	1.05	1	0.306
	Attractiveness of the view	12.53	1	0.000**
	Air temperature	4.86	1	0.027
CGI	CGI	38.42	1	0.000***
	Socio-environmental context	4.23	3	0.237
	Chronotype	2.61	2	0.271
	Self-assessed glare sensitivity	9.00	1	0.003*
	Iris pigmentation	1.71	1	0.190
	Attractiveness of the view	9.68	1	0.002**
	Air temperature	5.12	1	0.024
DGI	DGI	31.67	1	0.000***
	Socio-environmental context	6.23	3	0.101
	Chronotype	2.52	2	0.284
	Self-assessed glare sensitivity	9.66	1	0.002**
	Iris pigmentation	1.88	1	0.171
	Attractiveness of the view	9.16	1	0.002*
	Air temperature	5.82	1	0.016
E_v	E_v	35.03	1	0.000***
	Socio-environmental context	2.14	3	0.544
	Chronotype	2.31	2	0.316
	Self-assessed glare sensitivity	8.40	1	0.004*
	Iris pigmentation	0.59	1	0.442
	Attractiveness of the view	12.17	1	0.000**
	Air temperature	4.70	1	0.030
L_{mean}	L_{mean}	37.91	1	0.000***
	Socio-environmental context	1.81	3	0.613
	Chronotype	2.47	2	0.291
	Self-assessed glare sensitivity	7.11	1	0.008*
	Iris pigmentation	0.97	1	0.325
	Attractiveness of the view	12.00	1	0.001**
	Air temperature	3.79	1	0.052

Table 7.4: Results of the LRT to assess the statistical significance of each of the independent variables of the multiple logistic regression models to predict the binary glare report; a corrected significance level of $\alpha = 0.01$ is applied

None of the results of the LRT are statistically significant ($\chi^2(df = 1) < 4$, $p > 0.05$), which means that no interaction term is required in the model.

To visualize how the two factors might influence discomfort glare perception, the logistic growth curves of two multiple logistic regression models based on the DGP and each of the two factors (Equations 7.3 and 7.4) are presented in Figures 7.5 and 7.6. The multiple logistic regression models for the four other metrics are available in Appendix G.

$$\text{Subj. assessment } \Big[0|1\Big] \sim DGP + \text{ Self-assessed glare sensitivity} \tag{7.3}$$

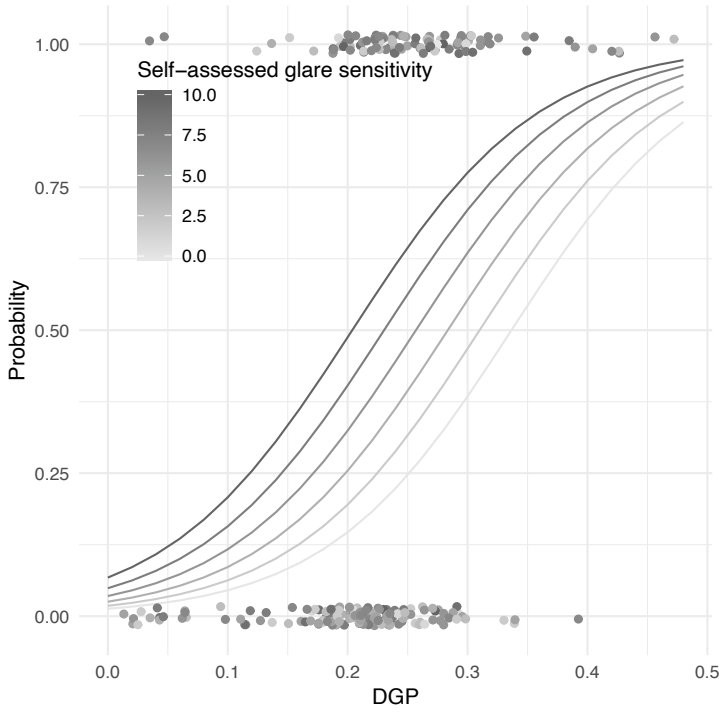


Figure 7.5: Logistic growth curve of the multiple logistic regression model based on the DGP and the self-assessed glare sensitivity of the subject to predict the binary glare report

The multiple logistic regression model derived from the collected

data and displayed in Figure 7.5 suggests that the more sensitive to glare the subject assesses her/himself, the lower is the DGP value at which he/she will report discomfort glare.

$$\text{Subj. assessment}\left[0|1\right] \sim DGP + \text{Attractiveness of the view} \quad (7.4)$$

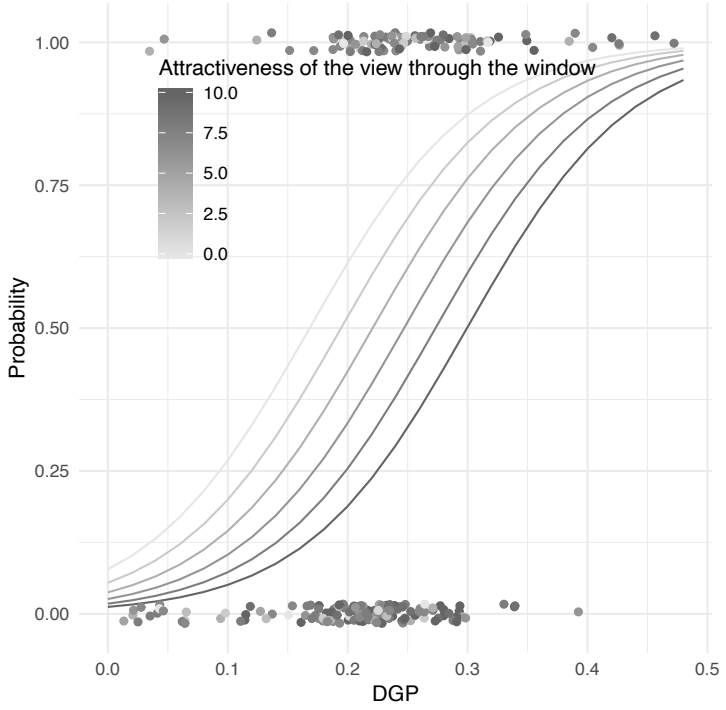


Figure 7.6: Logistic growth curve of the multiple logistic regression model based on the DGP and the attractiveness of the view through the window to predict the binary glare report

The multiple logistic regression model derived from the collected data and displayed in Figure 7.6 suggests that the higher the subject assesses the view through the window that he/she has from his/her office desk, the higher is the DGP value at which he/she will report discomfort glare.

7.3.2 Discussion

Firstly, the three additional factors that were not equally distributed between the four socio-environmental contexts, i.e., chronotype, iris pigmentation, and the attractiveness of the view through the window, are tested for their potential confounding effect on the socio-environmental context.

The other factors showed a relatively similar distribution across the four socio-environmental contexts (Figures 6.2 and 6.3). Therefore, if these other factors had had a confounding effect on the socio-environmental context, it would not matter since the effect would be the same for the four socio-environmental contexts.

The three factors indicated a potential confounding effect on the socio-environmental context when testing the amount of adjustment of the parameters. However, no statistically significant influence of the socio-environmental context on the subjective assessments of discomfort glare could be detected in the multiple logistic regression models controlling for the potentially confounding factors.

Consequently, the data collected and analyzed in this research does not provide evidence to support an influence of the socio-environmental context on discomfort glare perception, although the chronotype, iris pigmentation, and view through the window might have confounded the relationship between the socio-environmental context of a subject and her/his subjective assessment of discomfort glare. Future studies on the influence of the socio-environmental context on discomfort glare perception should consider these three potentially confounding factors. Furthermore, a rigorous assessment of these factors, such as resorting to the MCTQ to evaluate the chronotype of the subject, could clarify their confounding effect on the socio-environmental context.

Secondly, the five selected additional factors are tested for collinearity before investigating their potential influence on discomfort glare perception from daylight. Neither the visual analysis of the pairwise comparisons matrix nor the statistical test through the VIF analysis revealed any problem of collinearity between the independent variables. The multiple logistic regression analysis was therefore

performed for the five additional factors, the socio-environmental context, and each of the five metrics.

The results of the LRT (Table 7.4) suggest that two factors, i.e., the attractiveness of the view through the window and the self-assessed glare sensitivity of the subject, are statistically significant in predicting the binary glare report, in addition to the daylight discomfort glare metrics. Moreover, the deviance (χ^2) between the models with and without considering air temperature is non-negligible for all the models, although not statistically significant. This factor will be further investigated in the next section.

In Figure 7.6, the model based on the DGP and the attractiveness of the view through the window is graphically represented to give an idea of the influence that the attractiveness of the view through the window could have on discomfort glare perception: the more attractive is the view through the window according to the subject, the higher the discomfort glare stimulus at which he/she will report discomfort due to glare from daylight.

Although recent studies could not detect any influence of the view through the window [Hirning et al. 2014; Iwata et al. 2017b], this result is similar to what has already been observed several times in the literature. The more attractive, interesting, or important the view is through the window, the higher the tolerance towards discomfort glare from daylight [Osterhaus 2001; Wienold 2009a; Shin et al. 2012; Tuaycharoen et al. 2005; Tuaycharoen et al. 2007; Tuaycharoen 2011; Kent 2016]. As early as 1972, Hopkinson highlighted the conflict in making an assessment in a highly glaring situation when the view through the window was pleasant or interesting [Hopkinson 1972].

In Figure 7.5, the model based on the DGP and the self-assessed glare sensitivity is also graphically represented to give an idea of the influence that the self-assessed glare sensitivity could have on discomfort glare perception: the more a subject assessed her/himself as sensitive to glare, the lower the discomfort glare stimulus at which he/she will report discomfort due to glare from daylight.

In the literature, some studies support this result, and show a lower

tolerance to discomfort glare or a higher frequency of reports of discomfort glare for subjects assessing themselves as glare-sensitive [Saur 1969; Osterhaus 2001; Rodriguez et al. 2014]. However, other studies could not detect any statistically significant effect of the self-assessed glare sensitivity on discomfort glare perception [Kent et al. 2015a; Kent et al. 2015b; Inkarojrit 2005; Rodriguez et al. 2016b]. This might be due to the relatively small number of subjects in these studies ($\sim$ 30 subjects on average, against $\sim$ 250 subjects in this study), which might have allowed the collection of a sample representative of the distribution of glare sensitivity in the population.

Both the attractiveness of the view through the window and the self-assessed glare sensitivity present evidence of affecting discomfort glare perception from daylight. The aim of displaying the logistic growth curves of the models including these variables and derived from the collected data is to establish hypotheses that can be tested in future studies, thus to encourage further research on these factors. However, the parameters of the two multiple logistic regression models are not given, since these values should not be used (to modify existing discomfort glare metrics for instance) as the protocol of the study was not developed for such goal.

On another note, the absence of statistically significant influence of the other selected factors does not mean that these factors should not be further studied. The field study was indeed not designed to specifically investigate these factors, and a small effect of one of these factors might not have been detected. For instance, the fact that both the chronotype and glare sensitivity were self-assessed through a unique question could have brought noise into the data, preventing the detection of a small effect of these factors. A more precise classification of the subjects and a uniformly distributed dataset would be more appropriate to study the influence of this factor on discomfort glare perception from daylight.

7.4 The Special Case of Thermal Factors

In Section 6.5, a qualitative analysis of the subjective assessments of discomfort glare from daylight made through the OEQ led to the observation that there is an association between daylight and thermal discomfort in the Chilean context, which could have biased the subjective assessments. This association seems to make the Chilean subjects less tolerant towards discomfort glare from daylight due to their negative thermal expectations related to daylight. As a consequence, it is hypothesized that daylight discomfort glare and thermal factors interact in affecting subjects' perception.

Since buildings are multi-sensory environments, interactions between environmental factors most likely play a role in affecting building occupants' perception. A recent review study shows that research is still very limited on this topic, namely on the combined effect of environmental factors, but that environmental factors most probably interact with each other [Torresin et al. 2018].

This section aims to investigate whether a quantitative analysis of the collected data supports the presence of an interaction between daylight discomfort glare and air temperature, which would affect the subjects' discomfort glare perception and/or thermal sensation.

Furthermore, as the association between daylight and thermal discomfort has been observed in particular in the Chilean context, it is interesting to test whether there is evidence of such an interaction in the other socio-environmental contexts. For this reason, the analyses in this section are performed for each socio-environmental context separately. Consequently, the subjects of which the data is used have to be acclimatized to one of the four socio-environmental contexts.

Since the analyses in this section are based on the subjective assessments of glare made through the OEQ, the datasets to which the analyses in this section are applied are those presented in Table 6.7. In these datasets, the E_v outliers, i.e. the data points for which the sun was in the FOV, have been removed, but the data points of the Chilean socio-environmental context for which the answer

to the OEQ exhibits a visual/thermal ambiguity remain included. The reason for including these ambiguous data points is that these subjects are probably the most apparently affected by a potential interaction between daylight discomfort glare and air temperature.

7.4.1 Analyses and Results

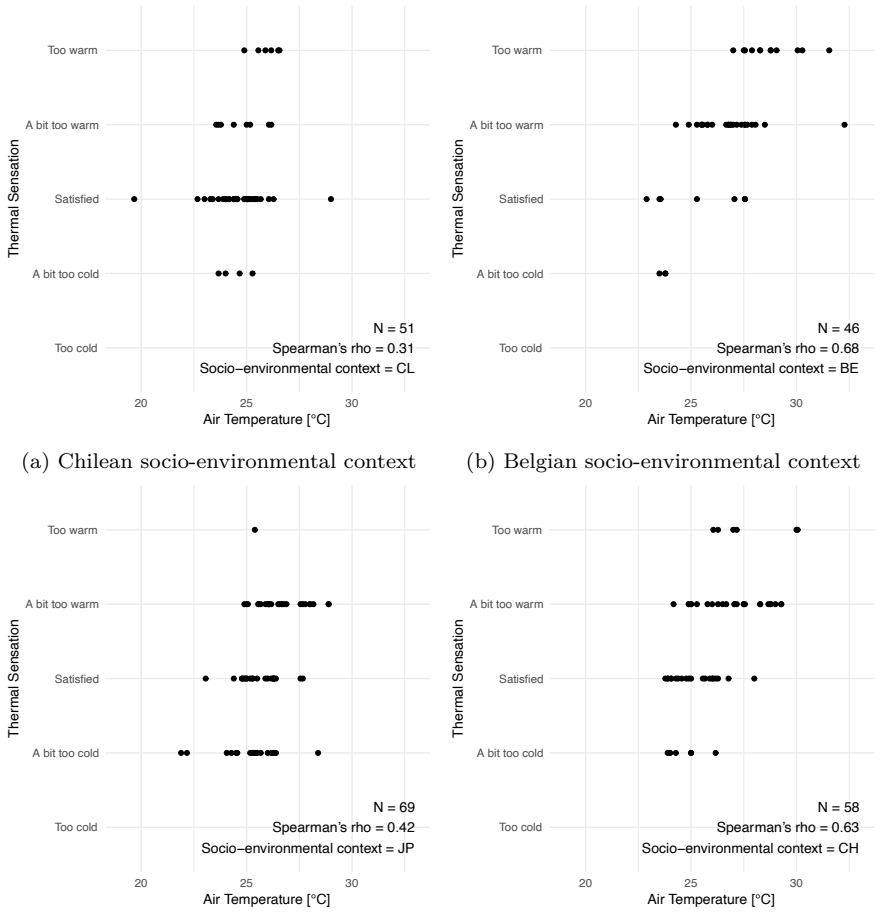
The correlation between the air temperature and the thermal sensation is evaluated for each socio-environmental context through the Spearman's rank correlation coefficient. The aim is to assess whether the correlations are similar in the four contexts, which would imply that other thermal factors than the air temperature, such as the humidity or the air speed [ASHRAE 2013], are most probably evenly distributed across the different contexts. Scatter plots of the thermal sensation according to the air temperature, as well as the correlation coefficients, are available in Figure 7.7.

The correlation coefficients of the Chilean and Japanese contexts are much lower than those of the Belgian and Swiss contexts. Indeed, the Chilean and Japanese data indicates a practically significant effect of air temperature on thermal sensation, whereas the Belgian and Swiss data indicates a moderate effect.

These results could suggest that other thermal factors than air temperature, such as the air speed or the clothing insulation, have different distributions in the Chilean and Japanese contexts, which affect thermal sensation, causing a lower correlation with air temperature.

However, the low correlation coefficients in two contexts could also be due to non-equivalent distribution of air temperature in the four contexts, or to a confounding effect on thermal sensation, in some contexts, by some extraneous variable, such as daylight discomfort glare. These three potential explanations are discussed in the next subsection.

Statistical tests are then performed to assess whether some interactions between daylight discomfort glare and air temperature can be observed quantitatively. To observe an interaction between these environmental factors, the subjects' perception of one of the envi-



(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

Figure 7.7: Spearman's ρ correlation coefficients between the air temperature and the thermal sensation, and scatter plots of the ratings of thermal sensation in function of the air temperature for the four socio-environmental groups

ronmental factors has to be demonstrated as being influenced by the other one.

Firstly, the influence of the air temperature, i.e., a thermal factor, on the binary glare report, i.e., the subject's perception of daylight discomfort glare, is tested through Wilcoxon rank sum tests for each socio-environmental context.

The Wilcoxon rank sum test, also called Wilcoxon-Mann-Whitney test, is a nonparametric test that compares the medians of a continuous variable, i.e., the air temperature, for two independent groups, i.e., the subjects who reported glare, and those who did not.

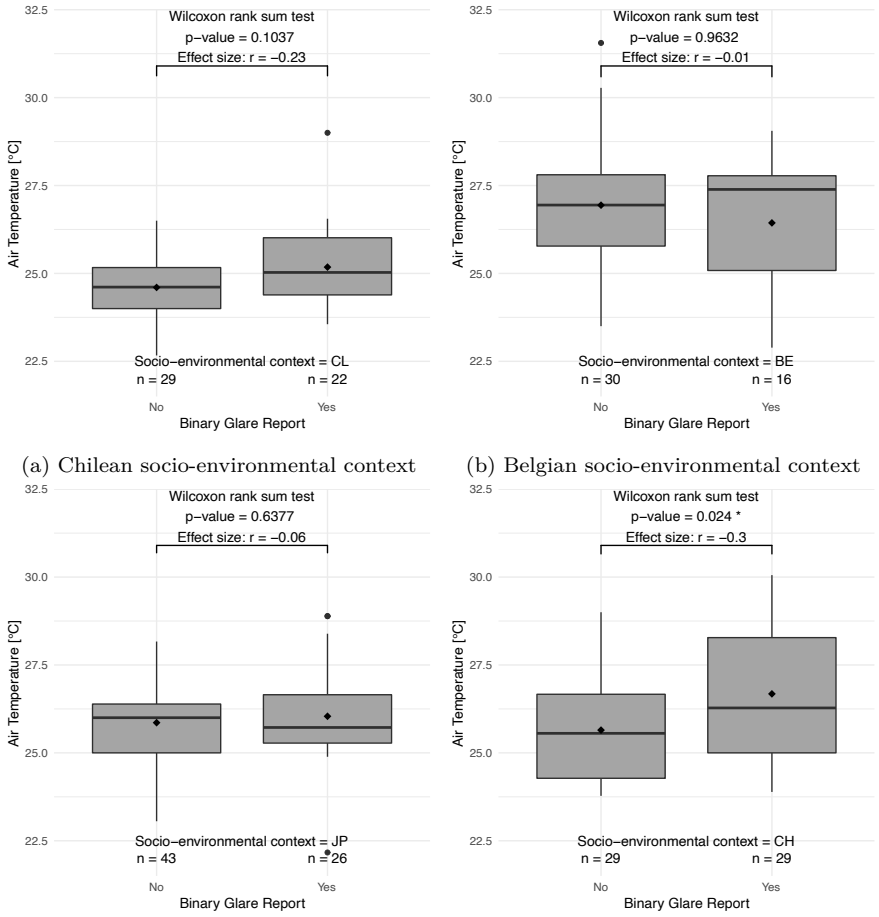
The null hypothesis that is being tested establishes that the location of the median does not shift in the distributions of the two groups. The Wilcoxon rank sum test assesses thus whether the medians of air temperature differ significantly between the subjects reporting glare and those who do not, in each context. This test is the nonparametric equivalent to the independent samples t-test, which could not be applied since the assumption of normal distribution was not met for each group, as found out through the Shapiro–Wilk test [Field et al. 2012].

The results of the Wilcoxon rank sum test for the influence of the air temperature on daylight discomfort glare perception, which is evaluated through the binary glare report, are given in Figure 7.8.

The results of the Wilcoxon rank sum test of the influence of the air temperature on the binary glare report indicate a statistically significant and practically relevant relationship between the two variables in the Swiss context. There are no statistically significant relationships in the three other contexts.

Moreover, a visual inspection of the boxplots in Figure 7.8 suggests that higher air temperatures in the Swiss context lead to more reports of discomfort glare from daylight.

It should be noted that a more discomforting environment due to daylight discomfort glare is likely related with higher air temperature, since more daylight means more solar loads heating the space.



(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

Figure 7.8: Results of the Wilcoxon rank sum test for the influence of air temperature on the binary glare report (a corrected significance level of $\alpha = 0.01$ is applied), and box plots representing the distribution of the data for the air temperature per categories in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

To verify that the influence of the air temperature on discomfort glare perception in the Swiss context is not due to higher levels of daylight discomfort glare, a Wilcoxon rank sum test is performed to test the relationship between E_v, i.e., one of the daylight discomfort glare metrics, and air temperature. Since the Wilcoxon rank sum test compares the means of a continuous variable for two independent groups, each of the four datasets has to be separated in two groups depending on the air temperature. The median air temperature in each dataset is used as the threshold to split the datasets in two groups.

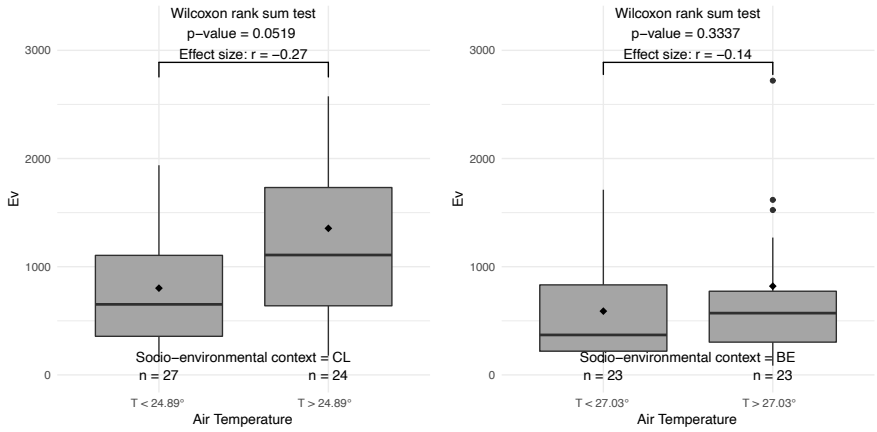
The results of this second Wilcoxon rank sum test are given in Figure 7.9.

Results of this second Wilcoxon rank sum test indicates no statistically significant nor practically relevant relationship between the air temperature and the level of daylight discomfort glare represented by E_v in the Swiss context. There is, however, a difference of practical relevance, but not statistical significance, between the levels of daylight discomfort glare in the two air temperature groups in Switzerland, as the boxplots in Figure 7.9a indicate that higher vertical illuminance levels are related to higher air temperatures.

Secondly, the influence of daylight discomfort glare on thermal sensation, i.e., the subject's perception of the thermal factors, is tested. This test is conducted through Wilcoxon rank sum tests investigating the influence of each of the five daylight discomfort glare metrics, which represent daylight discomfort glare, on thermal sensation for each socio-environmental context.

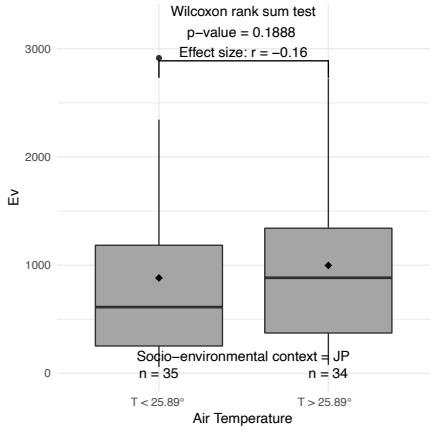
The aim is to observe whether the interaction could go into both directions, namely whether daylight discomfort glare would influence thermal sensation in some contexts in the same way air temperature seems to influence daylight discomfort glare perception in the Swiss context.

Since the Wilcoxon rank sum test compares the medians of a continuous variable for two independent groups, the thermal sensation variable has to be transformed into a binary variable. The association observed in Section 6.5 implies that daylight is linked with

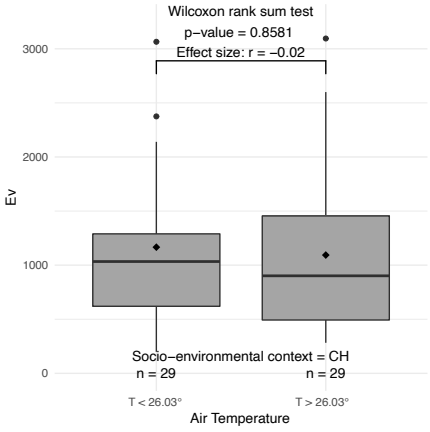


(a) Chilean socio-environmental context

(b) Belgian socio-environmental context



(c) Japanese socio-environmental context



(d) Swiss socio-environmental context

Figure 7.9: Results of the Wilcoxon rank sum test for the relationship between E_v and air temperature (a corrected significance level of $\alpha = 0.01$ is applied), and box plots representing the distribution of the data for E_v per categories in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

too warm a thermal sensation. The A bit too warm and Too warm categories are therefore grouped in the new Too warm category, and the Satisfied, A bit too cold and Too cold categories in the new Not too warm category.

Moreover, since the tests are conducted for the five metrics, the Bonferroni correction must be applied.

The results of the Wilcoxon rank sum tests, assessing whether the medians of each metric differ significantly between the Not too warm and Too warm groups for each context, are given in Figure 7.10 for the DGP. The tests for the other metrics are available in Appendix G.

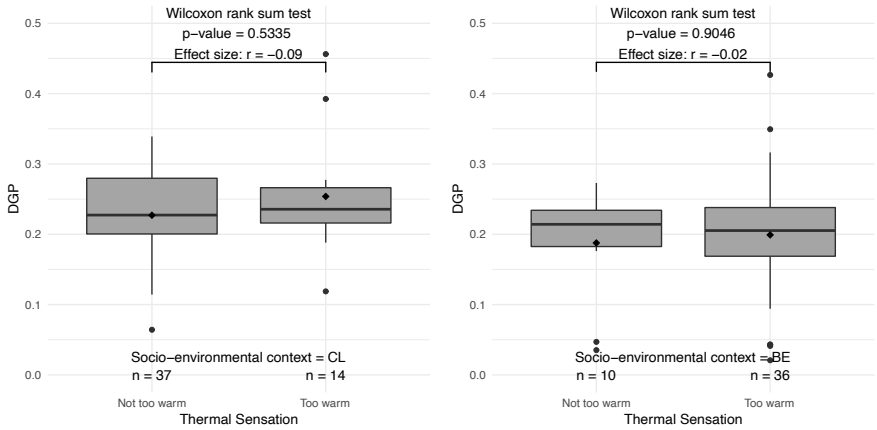
The results of the tests indicate no statistically significant influences of the level of daylight discomfort glare on thermal sensation. The effect size of the relationship between saturation-based metrics and thermal sensation in the Japanese context is at the borderline of practical relevance, but as there is no statistical significance, no further observations can be made.

Finally, the influence of the thermal sensation, i.e., the subject's perception of thermal factors, on the binary glare report, i.e., the subject's perception of daylight discomfort glare, is tested through Fisher's exact tests for each socio-environmental context.

Fisher's exact tests evaluate whether there is a relationship between two categorical variables. The null hypothesis that is being tested establishes that there is no difference in the proportions of one variable between the groups of the other variable. This nonparametric test replaces the chi-squared test here, since the latter relies on a χ^2 distribution, which is not appropriate when one or several groups have fewer than five data points [Field et al. 2012].

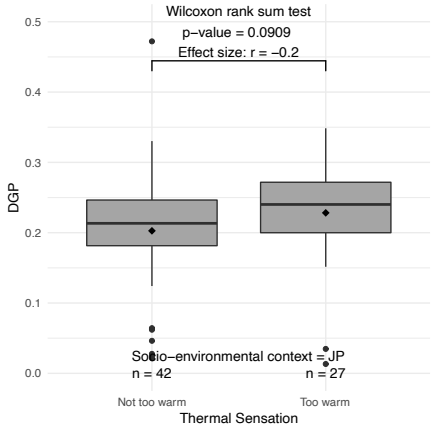
In other words, the Fisher's exact test is conducted to assess whether the proportion of each thermal sensation rating differs significantly between the No glare report and Glare report groups derived from the OEQ in each socio-environmental context. The results of this test are given in Figure 7.11.

As expected, the relationship between thermal sensation and dis-

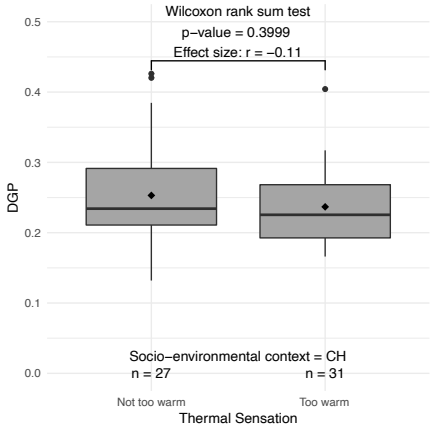


(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

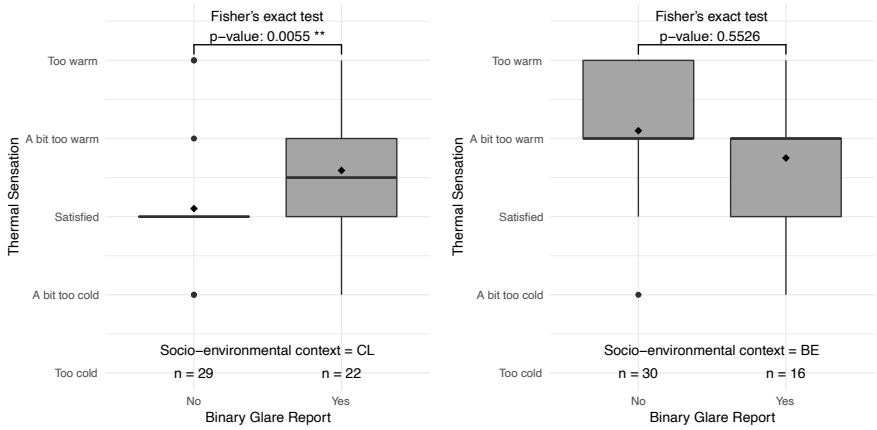


(c) Japanese socio-environmental context



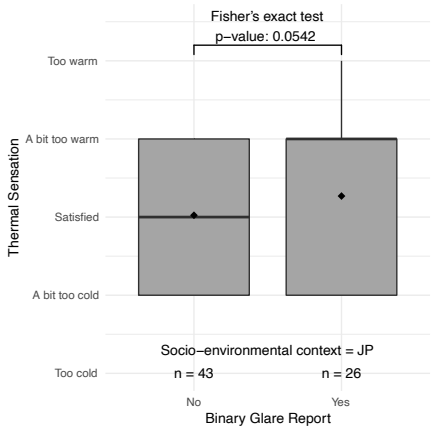
(d) Swiss socio-environmental context

Figure 7.10: Results of the Wilcoxon rank sum test for the influence of the DGP on thermal sensation (a corrected significance level of $\alpha = 0.01$ is applied), and box plots representing the distribution of the data for DGP per categories in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

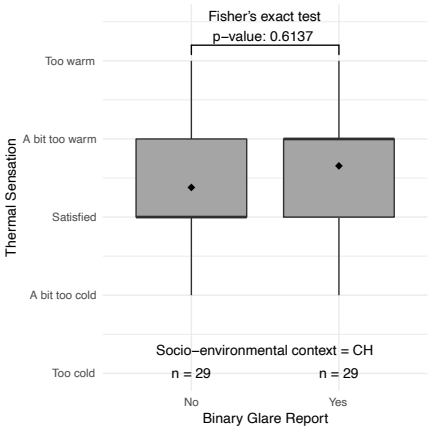


(a) Chilean socio-environmental context

(b) Belgian socio-environmental context



(c) Japanese socio-environmental context



(d) Swiss socio-environmental context

Figure 7.11: Results of the Fisher's exact test for the relationship between daylight discomfort glare perception and thermal sensation (a corrected significance level of $\alpha = 0.01$ is applied), and box plots representing the distribution of the data for thermal sensation per categories in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

comfort glare perception represented by the binary glare report is statistically significant in the Chilean context. There seems to be no such relationships in the three other contexts, as the results indicate no other statistically significant differences.

7.4.2 Discussion

In this section, a potential interaction between daylight discomfort glare and thermal factors was investigated. This interaction has been hypothesized following the qualitative analysis of the answers to the OEQ of the Chilean socio-environmental group. Recent literature seems also to support interactions between environmental factors [Torresin et al. 2018], and especially between visual and thermal factors [Chinazzo 2019].

The interaction is studied through nonparametric statistical tests applied separately for each context, as it is suspected that the interaction might not be detected or might not be similar in each socio-environmental context.

First, the correlations between thermal sensation and air temperature differ significantly between the socio-environmental contexts. The correlation coefficients of the Chilean and Japanese contexts are much lower than those of the Belgian and Swiss contexts. Three potential explanations are considered.

A first explanation is the non-equivalent distributions of air temperature in the four contexts. The boxplots of the air temperatures experienced by the subjects during the study (Figure 7.12) show that these differ from one socio-environmental context to the next.

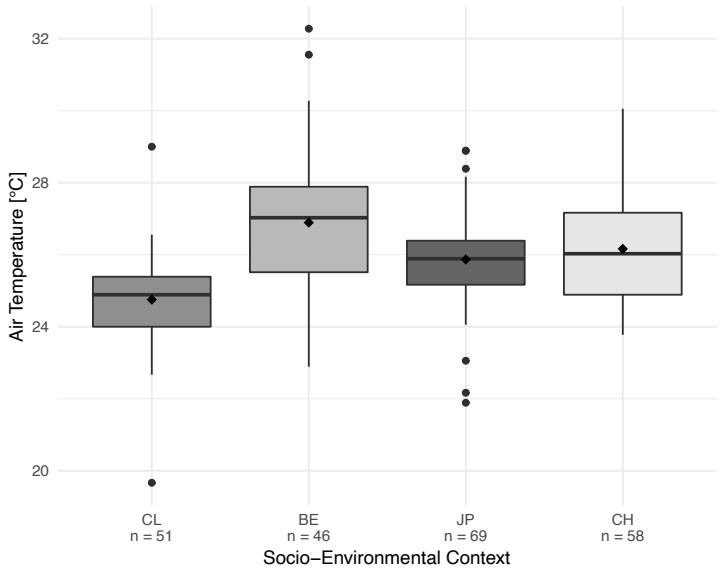


Figure 7.12: Box plots representing the distribution of the data for the air temperature experienced by the subjects during the study in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

In the Belgian context, the air temperatures are the highest, for most days with clear sky conditions happened during the heatwave at the beginning of summer 2017. Conversely, the air temperatures are relatively low in the Chilean context. None of the studied buildings from the Chilean context benefited from air conditioning, but occupants had become accustomed to working with closed shading devices to protect themselves from the heat gains brought by solar radiation. Moreover, the ranges of air temperatures measured in the Chilean and Japanese contexts are most probably too narrow to observe diversified thermal sensations ($SD = 0.98°$ C for CL, and $SD = 0.82°$ C for JP, compared to $SD = 1.85°$ C for BE, and $SD = 1.74°$ C for CH).

However, this first explanation considers that thermal sensation is only influenced by air temperature, whereas several other factors play a role. The low coefficients could also be due to another thermal factor such as the air speed or the clothing insulation.

These other thermal factors might have different distributions in the Chilean and Japanese contexts, which affect thermal sensation, causing a lower correlation with air temperature. None of these other thermal factors were recorded during the study except for the relative humidity. The mean of the relative humidity is slightly lower in the Japanese and Chilean contexts ($\mu_{JP} = 40\%$, $\mu_{CL} = 41\%$, $\mu_{BE} = 44\%$, $\mu_{CH} = 46\%$), but this difference should not be trusted as it falls in the sensor margin of error.

Lastly, the low correlation coefficients could indicate that thermal sensation is confounded in some contexts by an extraneous variable, such as daylight discomfort glare.

This third explanation was further studied through the statistical test looking at the influence of the level of daylight discomfort glare on thermal sensation. No statistically significant influences of the level of daylight discomfort glare, expressed through the metrics, on thermal sensation could be found. The results show thus no evidence of thermal sensation being confounded by daylight discomfort glare. These results are in line with those of a recent field study on the influence of light levels on thermal perception [Chinazzo et al. 2018]. In that study, subjects' thermal sensation was not influenced by light levels, although the thermal evaluation of the environment was.

Furthermore, the statistical test looking at the influence of the air temperature on daylight discomfort glare perception expressed through the binary glare report showed a statistically significant relationship in the Swiss context. The data suggests that higher air temperatures would lead to more reports of discomfort glare from daylight in this context. Moreover, this relationship should not be due to higher levels of daylight discomfort glare linked to higher air temperatures, as shown in Figure 7.9d. These results support an observation made in a recent study conducted in Switzerland, in which higher visual comfort scores were reported in the colder thermal condition in comparison to the warmer one [Chinazzo 2019].

However, no statistically significant relationships between the air temperature and daylight discomfort glare perception could be ob-

served in the results of the Chilean, Belgian, and Japanese groups.

Finally, no statistically significant relationship between thermal sensation and daylight discomfort glare perception was detected, except for the Chilean context. The data suggests that too warm thermal sensations are somehow linked to more reports of discomfort glare from daylight in this context. These results support the hypothesis that Chilean subjects tend to associate daylight and thermal discomfort. However, it can be observed in Figure 7.9a that higher levels of discomfort glare from daylight, expressed through E_v, might have been associated to higher air temperatures in this dataset, which would explain the association.

No general interaction between daylight discomfort glare and thermal factors could be observed in the results of this study. Nonetheless, some evidence seemed to indicate that the air temperature could have an influence on daylight discomfort glare perception in some socio-environmental contexts.

More research is required to understand how a potential interaction between daylight discomfort glare and thermal factors would pan out. Further studies would be especially useful in contexts where overheating due to sunlight radiation is a recurrent issue. Indeed, although no hypotheses can be established based on these results, some tendencies in the data seem to imply that higher air temperatures, and thus too warm thermal sensations, would increase the sensitivity to discomfort glare from daylight.

Furthermore, it is important to note that these results are based on data that were collected in a study that was not designed for this purpose. There are therefore several factors that might have weakened the likelihood of obtaining significant results.

For instance, the narrow ranges of air temperatures measured in the Chilean and Japanese contexts could be the reason why no significant relationships between air temperature and daylight discomfort glare perception could be observed. Moreover, the sensor used to measure the air temperature has a basic accuracy of $\pm 1°$ C, to which an error related to the varying location of the sensor relative to the subject should be added. A last example would be

the use of a non-conventional thermal sensation scale, instead of the one proposed by ASHRAE [ASHRAE 2013]. These three examples, and potentially other experimental biases, might have weakened the chances of showing an interaction.

In conclusion, the results presented in this section are aimed at raising awareness regarding potential interactions between environmental factors, rather than showing such interactions.

7.5 Conclusion

In this chapter, additional factors potentially influencing discomfort glare perception from daylight are studied to answer the first additional research question of the study. Among the 31 other factors listed in the state of the art (Section 2.2), only five were investigated, besides the socio-environmental context of the subject studied in Chapter 6.

From the five investigated factors, which are chronotype, self-assessed glare sensitivity, iris pigmentation, attractiveness of the view through the window, and air temperature, the statistical analyses produced evidence suggesting a potential influence of three factors on the subjective assessment of discomfort glare from daylight.

Although no conclusions can be drawn on the influence of these factors since the protocol of the study was not defined for such a goal, the results of the analyses regarding the three factors, listed below, lead to the following hypotheses:

- **Self-assessed glare sensitivity**: the more a subject assesses her/himself as sensitive to glare, the lower the discomfort glare stimulus at which he/she will report discomfort due to glare from daylight
- **Attractiveness of the view through the window**: the more attractive a subject assesses the view through the window, the higher the discomfort glare stimulus at which he/she will report discomfort due to glare from daylight
- **Air temperature**: in the Swiss socio-environmental context, the higher the air temperature, the more the subject will report discomfort glare from daylight

These hypotheses are established to support the development of future studies, which should be dedicated to investigating each of these factors separately by developing a proper protocol of study for each.

If these hypotheses were demonstrated to be true, this could have two major implications.

On the one hand, an influence of the view through the window and of the air temperature on discomfort glare perception would imply that environmental factors interact in affecting building occupants' perception. These interactions could be complex in view of the numerous potential environmental factors.

For instance, a building occupant who considers her/his view through the window attractive is assumed to be more tolerant towards discomfort glare from daylight. Furthermore, a building occupant who feels too warm, due to high air temperatures, is assumed to be less tolerant towards discomfort glare from daylight. But these two interactions could be antagonistic in some cases, since a view out could imply solar loads and passive heating through the glass. What would then be the final combined effect of these interactions on the occupant's discomfort glare perception from daylight?

In this regard, demonstrating an influence of the view through the window or the air temperature on discomfort glare perception could develop in a high interest for the combined effects of environmental factors on building occupants' perception, as well as for mitigation effects. A mitigation effect implies that the interaction of one environmental factor with another one could be used to improve the perception of the latter by the occupant. In the literature for instance, this approach has already been considered to mitigate the perception of thermal discomfort through the color of lighting [Huebner et al. 2016].

On the other hand, an influence of the self-assessed glare sensitivity on discomfort glare perception would imply that there exists a simple way of explaining, in part, the high variation between subjects' discomfort glare perception.

Over 70 years ago, the large variation in discomfort glare perception between subjects was already acknowledged, and assumed to be related to numerous physiological and psychological factors [Luckiesh et al. 1949]. Since then, there have been many attempts to explain this variation, but there is still no validated way of justifying why there is this variation.

Although it would not help in explaining why there is this varia-

tion, demonstrating an influence of the self-assessed glare sensitivity on discomfort glare perception could provide an efficient way to improve the prediction of subjects' discomfort glare perception, by taking into account the variation in their sensitivity. The subjects themselves are most probably the best informed to determine whether they are sensitive to discomfort glare, on the condition that they understand correctly what discomfort glare is.

Moreover, self-assessed glare sensitivity would require much fewer resources to evaluate than glare sensitivity evaluated through an objective test. However, self-assessed glare sensitivity would not be as precise as objectively evaluated glare sensitivity, and would never be accurate enough such that it can account for the entire variation between subjects' discomfort glare perception. Nevertheless, it was demonstrated from a laboratory study [Van Den Wymelenberg 2012b] that subjects were able to correctly classify themselves into the sensitive or non-sensitive categories, by comparing the self-assessed glare sensitivity to the objectively evaluated one. However, they could not reliably judge, on a multiple-point scale, their level of sensitivity to discomfort glare .

As long as the mechanism of discomfort glare perception is not understood and there exist no simple ways of defining objectively a subject's glare sensitivity, the self-assessed glare sensitivity, if its influence is proven, would be the most efficient way of providing better evaluation of discomfort glare perception.

In conclusion, the hypotheses established regarding the self-assessed glare sensitivity, the attractiveness of the view through the window, and the air temperature need to be tested in dedicated studies, of which the protocol is defined in accordance to those specific goals. Although the analyses of the data conducted in this chapter provided some evidence of the influence of these factors on discomfort glare perception from daylight, the nature of the first additional research question was exploratory research, and no conclusions can be drawn from this evidence.

Chapter 8

Results: Second Additional Research Question

8.1 Introduction

In Chapter 6, the main research question of the study was tackled, as the influence of the socio-environmental context on discomfort glare perception from daylight was investigated based on the collected data. The results show no evidence of an influence of the socio-environmental context on discomfort glare perception from daylight in office buildings, but highlight two issues in the data.

Firstly, the subjective assessments made via the glare rating scales in the Japanese context could not be predicted by the daylight discomfort glare metrics (Section 6.4). The evidence collected in the data analyzed led to the hypothesis that the subjective assessments made via the glare rating scales (A, B, and C) in the Japanese context were biased, as it seemed that the translation of "glare" in Japanese was not appropriate, hence not understood by the subjects.

Other types of bias could have affected the subjective assessments of discomfort glare, however, whether for the Japanese group or for the other ones. Some recent publications have indeed drawn the attention on several issues that could bias the subjective assessments of discomfort glare [Fotios 2018; Kent et al. 2018c; Allana et al. 2019]. To look deeper into these issues, the subjective assessments of discomfort glare collected via different methods during this study are compared and analyzed in Section 8.2.

Secondly, a small difference was observed between the results of this field study and those reported from several laboratory studies (Section 6.3). This observation seems to imply that the metrics perform better in predicting the subjective assessments of the subjects in office-like laboratory cells than of those in real offices. To investigate whether there is a difference in discomfort glare perception between field and laboratory studies, the results of two laboratory studies similar to this field study are analyzed and compared in Section 8.3.

These two issues are the focus of the second additional research question, as it aims at determining whether some of the potential

experimental biases identified from the literature have a probable influence on the results of studies on discomfort glare perception. Two of these potential experimental biases are indeed the glare rating scales and the study type. The purpose of the second additional research question is therefore to analyze the data regarding these potential experimental biases, and indicate whether they could affect the results of studies on discomfort glare perception.

For the results presented in this chapter, the statistical tests are completed with the software R version 3.5.2 [R Core Team 2018], as well as:

- the R package *psych* version 1.8.12 [Revelle 2018] for the Cronbach's α evaluations;
- the R package *ROCR* version 1.0-7 [Sing et al. 2005] for the ROC curve analyses.

8.2 Subjective Assessment Method

As explained in Subsection 4.1.5, two main methods are currently used to collect subjective assessments of discomfort glare, the glare rating scale and the drawing-based question. The more common of the two methods, which is also the easiest to implement, is to ask a subject to rate the amount of discomfort glare, or of discomfort due to glare, that he/she perceives from a visual scene on a glare rating scale.

Many different glare rating scales have been used in the literature. Most of them are replications or derivatives of two well-known scales, the 4-point Hopkinson's glare rating scale [Hopkinson 1940], and the 9-point (but 5 descriptors) De Boer's glare rating scale [De Boer 1967]. Nowadays, one of the most adopted glare scales is the 4-point Osterhaus' scale [Osterhaus et al. 1992], but modified versions of the De Boer's scale are also common.

The large diversity of existing glare rating scales, and the lack of studies on the biases induced by these scales cause confusion among researchers about which scale to use. Different scales are then implemented in different studies, and sometimes a new scale is even created. This practice makes between-studies comparison very difficult, which can, on the long-term, impact research quality.

In the literature, there seems to be only one study investigating subjects' interpretation of a modified De Boer's scale [Gellatly et al. 1990]. The results show that, besides the confusion brought by the terminology of the scale labels, only 15% of the subjects could reconfigure these labels in the right sequence.

Moreover, several common issues related to the collection of subjective assessments of discomfort glare through category rating scales, thus glare rating scales, have been highlighted [Fotios 2018], as these issues most probably bias the data, and lead to unreliable conclusions. When collecting subjective assessments of visual factors, "*it is not only the stimulus that matters but also the way in which the question is asked*" [Fotios 2018].

The aim of this section is to compare three different glare rating

scales (A, B, and C) and an OEQ that have been used as subjective assessment methods of discomfort glare in this study, and to investigate whether these different methods are interpreted by the study subjects as it is expected.

Only the fourth cleansing rule described in Section 4.3, which controls for acquiescence response bias, is applied on the dataset used for these analyses since only the subjective assessments of the subjects are needed. However, the subjective assessments made on the glare rating scales (A, B, and C) by the Japanese subjects as well as the ambiguous answers to the OEQ given by some Chilean subjects are removed from the dataset, as it has been shown that these subjective assessments cannot be predicted by the metrics and could be biased (Sections 6.4 and 6.5).

The full dataset, described in Table 8.1, contains 553 subjective assessments of discomfort glare, of which two might be from the same subject. Indeed, each subject did two discomfort glare evaluations; one in the actual lighting conditions he/she was working in when the investigator arrived, and one in the maximized daylighting conditions, to increase the occurrence of discomfort glare perception from daylight.

Dataset	N	First glare evaluation	Second glare evaluation
Total	553	278	275

Table 8.1: Information on the dataset (Japanese and ambiguous data points removed) used for the analysis of the subjective assessment methods (Section 8.2)

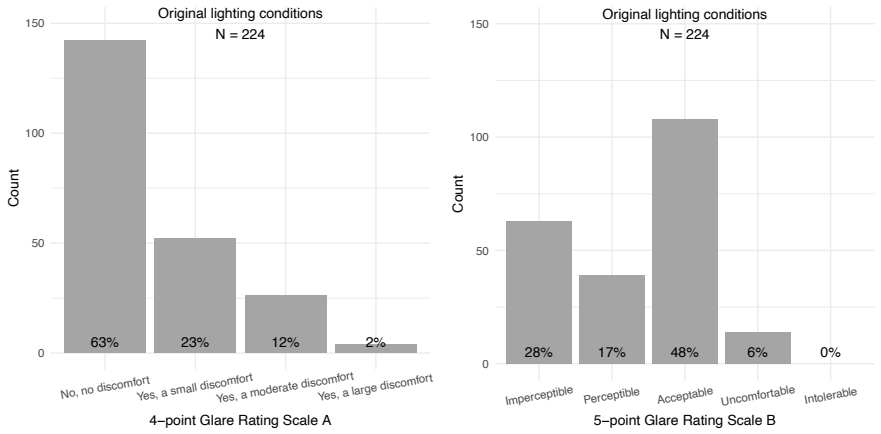
The descriptive statistical analyses in this section are each based on a subset of the full dataset in Table 8.1. Firstly, it is much easier to interpret between-subjects analyses than a combination of within- and between-subjects analyses. Hence, it is preferable that each subset used in the analyses contains only the evaluation of one visual scene per subject. Secondly, all three subjective assessments made on each glare rating scale are not available for each subject; only the 4-point scale A was used systematically for all the subjects and for the two discomfort glare evaluations. For these reasons, different subsets of the full dataset are used depending on the analyses

and the subjective assessment method studied.

8.2.1 Analyses and Results

Glare rating scales are usually seen by researchers as unipolar scales, going from "no glare" to a "very glary" end. The researchers treat them as such in their analyses, especially for their correlation with discomfort glare metrics.

To assess whether the glare rating scales A and B are interpreted as unipolar scales by the subjects in this study, the distribution of the subjective assessments made on these scales by each subject for their first discomfort glare evaluation are analyzed in Figure 8.1. Since the first discomfort glare evaluation was made in the lighting conditions in which the subject was working, it is expected that a large majority of the visual scenes will be rated as comfortable. The distributions of the ratings on these two scales are therefore expected to be right skewed.



(a) 4-point glare rating scale A (b) 5-point glare rating scale B

Figure 8.1: Bar plots representing the distribution of the subjective assessments made on the glare rating scales A and B during the first discomfort glare evaluation

It should be noted that the distributions shown in Figure 8.1 are based on a dataset of 224 subjects, instead of the first 278 glare evaluations displayed in Table 8.1. Half of the Swiss subjects had

two labels switched on purpose in the 5-point glare rating scale B, for reasons explained on p.419, and could therefore not be used in this comparison of distributions. Furthermore, the questions related to the glare scales A and B were not exactly the same; the first one (A) was asking about the perception of discomfort due to glare, whereas the second one (B) was asking about the rating of glare in the FOV.

A visual inspection of the distributions of the glare ratings on scales A and B indicates that these distributions are different. Therefore, the labels of these two scales were not interpreted in the same way by the subjects. Since both scales are supposed to go from "no glare" to a "very glary" end, at least according to how these scales are used in statistical analyses in the literature, the distribution of the ratings on scale A was expected.

The distribution of the ratings on scale B seems to be centered in the middle of the scale. Hence, the distribution resembles that of a bipolar scale, having a more symmetric distribution, rather than that of a unipolar scale, namely a usually asymmetric distribution.

Furthermore, the internal consistency between the two glare rating scales (A and B) is evaluated through the Cronbach's α [Tavakol et al. 2011]. The result shows that the two scales cannot be said to measure the same element, with a Cronbach's α of 0.66 (95% CI: $[0.56, 0.74]$). The recommended threshold for internal consistency is 0.8 [Nunnally et al. 1994].

To further investigate the difference in distribution between scale A and B, two potential explanations are hypothesized:

1. Most of the subjects interpreted the glare rating scale B as a bipolar scale due to the presence of a mid-point seen as the neutral option.
2. Most of the subjects were confused by the presence of two different concepts in the scale, namely acceptance and perception, leading to two potential ratings for comfortable scenes. Since the inclusion of a midpoint was demonstrated to decrease the extreme response style [Weijters et al. 2010], more subjects

picked the mid-point, Acceptable, instead of the extreme point, Imperceptible.

To test whether the first hypothesized explanation is sensible, a subset of subjects, selected at random, made their subjective assessment of discomfort glare on a modified version of the 5-point glare rating scale B, in which the Perceptible and Acceptable labels were switched. In the questionnaire answered by these randomly selected subjects, the question that followed the subjective assessment made on the 4-point glare scale A was therefore:

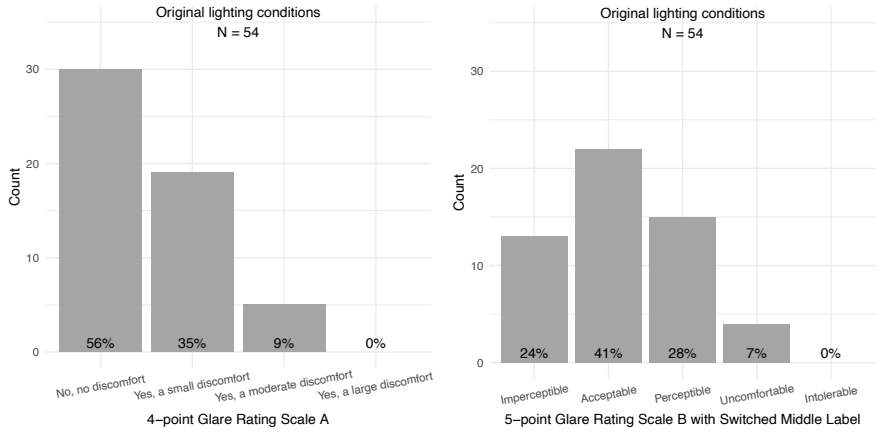
At the moment, how would you rate glare in your field of view?

- ○ Intolerable
- ○ Uncomfortable
- ○ Perceptible
- ○ Acceptable
- ○ Imperceptible

By switching two labels of scale B, it is expected that, if the subjects interpreted that scale as a bipolar scale due to the presence of a mid-point, the distribution of the modified 5-point scale B' would be similar to that of the original 5-point scale B.

The distributions of the subjective assessments made on the 4-point scale A and on the modified 5-point scale B' by the randomly selected subset of subjects for the first discomfort glare evaluation are presented in Figure 8.2. This subset of data is composed only of subjects from the Swiss socio-environmental context. The modified 5-point glare rating scale B' was implemented during the second year of the field study, i.e., for the Swiss and Japanese contexts, but the subjective assessments made on the glare rating scales of the Japanese subjects are not included in these analyses, as mentioned previously.

In Figure 8.2, the distribution of the glare ratings on the modified scale B' is slightly right skewed, although not exactly similar to that of the glare ratings on scale A. Moreover, the Cronbach's α between the scale A and the modified scale B' rises to 0.79 (95%



(a) 4-point glare rating scale A (b) Modified 5-point glare rating scale B'

Figure 8.2: Bar plots representing the distribution of the subjective assessments made on the glare rating scales A and B', of which two labels have been switched, during the first discomfort glare evaluation

CI: $[0.66, 0.89]$), which is just below the threshold for internal consistency.

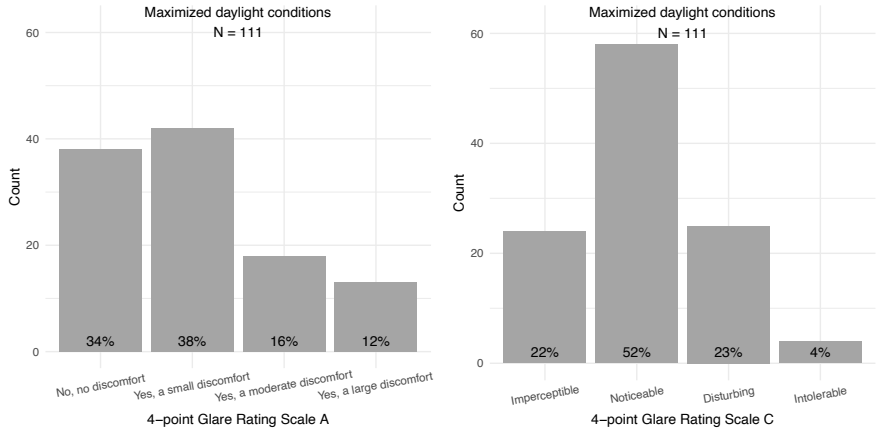
Although other causes might explain the difference in the distributions of the ratings on scale A and B, the previous results are in line with the second explanation, i.e., that the label Acceptable could have been confusing in the 5-point glare scale B, as it adds the concept of acceptance in a scale supposed to measure the perception of discomfort due to glare. There were thus two possible choices for comfortable scenes, i.e., Imperceptible and Acceptable, and both attracted some ratings of the subjects aiming for a no discomfort option.

The distributions of the subjective assessments made on the two 4-point glare rating scales A and C are also compared, to understand whether these scales are interpreted similarly by the subjects.

The subset of data used for the comparison is composed of subjects from only the Swiss socio-environmental context, since the glare rating scale C was only implemented during the second year of the field study. Furthermore, the subjective assessments made during

the second discomfort glare evaluation are used for this comparison, since the glare rating scale C was only asked in these conditions.

The distributions of the glare ratings made on the scales A and C are presented in Figure 8.3. These distributions are expected to be less right skewed than those for the ratings of the first glare evaluation, since these ratings are made under maximized daylighting conditions to increase the occurrence of discomfort glare from daylight.



(a) 4-point glare rating scale A (b) 4-point glare rating scale C

Figure 8.3: Bar plots representing the distribution of the subjective assessments made on the glare rating scales A and C during the second discomfort glare evaluation

While interpreting these results, it should be noted that the questions related to the glare scales A and C were not the same; one was asking about the perception of discomfort due to glare, whereas the second one was asking about the rating of glare in the FOV.

The graphs in Figure 8.3 present much more similar distributions than the previous ones. Furthermore, the Cronbach's α between the two 4-point scales (A and C) is 0.88 (95% CI: $[0.82, 0.91]$), which is above the threshold for internal consistency.

However, the distributions of the ratings are still not exactly similar.

The aim of daylight discomfort glare metrics, and thus of glare rating scales, is to determine whether there is discomfort due to glare

in a visual scene, i.e., whether or not the building occupant feels uncomfortable due to glaring lighting conditions. In this sense, the metrics help to decide whether actions should be taken to modify the lighting conditions.

With that in mind, and based on the distributions of the ratings in Figure 8.3, should we consider that 22% (Imperceptible), 34% (No, no discomfort), or 74% (Imperceptible + Noticeable) of the subjects did not perceive any discomfort due to glare, hence for whom no changes of the lighting conditions would have been required?

In the literature, the subjective assessments made on glare rating scales are often transformed to a binary variable of discomfort glare perception [Konis 2014; Wienold et al. 2019; Rodriguez et al. 2016a]. In this way, a cut-off value corresponding to the borderline between non-discomforting and discomforting scenes, most commonly referred to as the Borderline between Comfort and Discomfort (BCD), can be derived for each metric scale and used as a decision-maker to classify the visual scenes.

In view of the distributions of the ratings on the 4-point glare rating scales A and C in Figure 8.3, the location of this borderline, namely the BCD, is not obvious.

As mentioned in Subsection 4.1.5, the 4-point glare rating scale A contains a binary classifier, i.e. "No/Yes" present in the labels, allowing to discriminate between comfortable and uncomfortable situations related to discomfort glare. The BCD can therefore be set between the first and second levels of the 4-point scale A.

Alternatively, the BCD is usually set between the second and third levels of the 4-point scale C. Although there is a semantic issue with this setting since a visual discomfort is not necessarily disturbing, this BCD position seems the most logical in view of the scale labels, and was already used in several studies [Rodriguez et al. 2018; Rodriguez et al. 2016a; Van Den Wymelenberg et al. 2010].

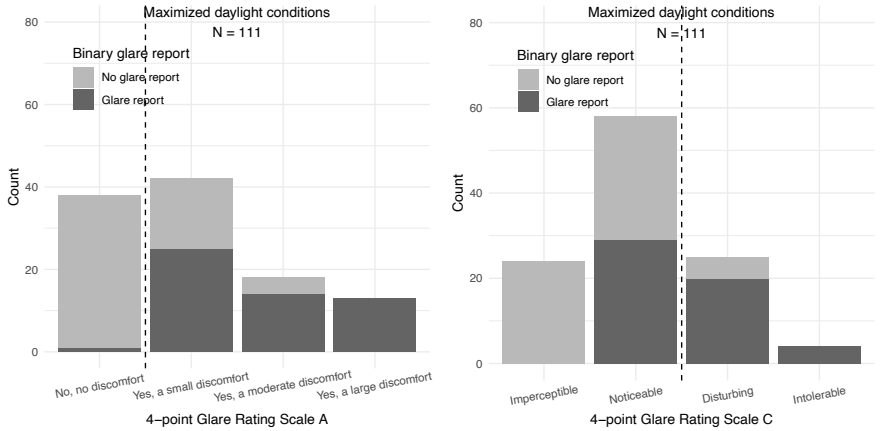
This would mean that two 4-point scales going from a not glaring category to a very glaring one have two different locations for the BCD: between No, no discomfort and Yes, a small discomfort for

the 4-point scale A, and between Noticeable and Disturbing for the 4-point scale C.

To further investigate these two potential borderlines, the subjective assessments made on these 4-point scales (A and C) are analyzed in relation to the binary glare report made through the OEQ.

The binary variable derived from this OEQ, i.e., the binary glare report, expresses whether or not a subject reported discomfort glare from daylight without being asked specifically about that issue. In other words, if the subject is in an uncomfortable situation due to the lighting conditions, he/she will report it through the OEQ, but otherwise, he/she will most probably not think about it and not report it.

The distributions of the ratings on glare scales A and C are displayed in relation to the binary glare report made for the same visual scene in Figure 8.4.



(a) 4-point glare rating scale A (b) 4-point glare rating scale C

Figure 8.4: Bar plots representing the distributions of the subjective assessments made on the glare rating scales A and C during the second discomfort glare evaluation in relation to the binary glare report derived from the OEQ

Regarding the 4-point scale A, the borderline defined by the "No/Yes" binary classifier does not match exactly with the binary glare report of the subjects. There is almost no Glare report on its left, but

some No glare report on its right (Figure 8.4a).

There could be several reasons to explain why 21 (19%) subjects having made No glare report in the OEQ ticked the Yes, a small discomfort or Yes, a moderate discomfort categories on glare scale A. For instance, the subject could have perceived some discomfort glare, but did not report it in the OEQ as the discomfort was slight and did not bother him. Or the subject wanted to please the investigator by reporting something on the glare rating scale. Or again, the imbalance in the labels of the glare scale A (with one "No" and three "Yes") could have incited the subject to report some discomfort in order not to pick the extreme category.

On another note, one subject reported some discomfort glare in the OEQ, but ticked the No, no discomfort category on the glare rating scale A. The inspection of the subject's answer to the OEQ about unsatisfying elements in the current lighting conditions, which is "*Not much. Maybe the contrast of light at the opposite wall.*", suggests that the subject was hesitant about the perceived discomfort. He/she seems to have answered something in the OEQ just because he/she was asked to. Although this observation is not significant, it might suggest that even the OEQ suffers from some response biases, as subjects feel that they have to report something although they would not have considered it as really discomforting.

Regarding the 4-point glare rating scale B, the borderline set between the Noticeable and Disturbing categories does not match with the binary glare report of the subjects, either.

With this borderline, the visual scenes for which 29 subjects (26%) made a Glare report through the OEQ (in which they were asked to report unsatisfying elements) are classified as comfortable visual scenes. No actions would thus be taken to modify the lighting conditions for more than half of the subjects who spontaneously complain about these lighting conditions.

Regarding this issue, Osterhaus already argued that setting the BCD between the Noticeable and Disturbing categories was inappropriate since the subjects obviously experience discomfort glare already as soon as it is rated Noticeable discomfort glare [Osterhaus

2008].

Alternatively, by setting the BCD between the Imperceptible and Noticeable categories, the visual scenes for which 39 subjects (31%) made No glare report through the OEQ would be classified as uncomfortable.

Lastly, the subjective assessments made on the 5-point scale B is also analyzed in relation to the binary glare report made through the OEQ. As scale B was implemented in the questionnaire for each socio-environmental context, the subjective assessments made for the second glare evaluation by the subjects in each context, except for Japanese subjects and subjects for whom two labels of the scale were switched, are included in the dataset.

The distributions of the ratings on glare scales B are displayed in relation to the binary glare report made for the same visual scene in Figure 8.5.

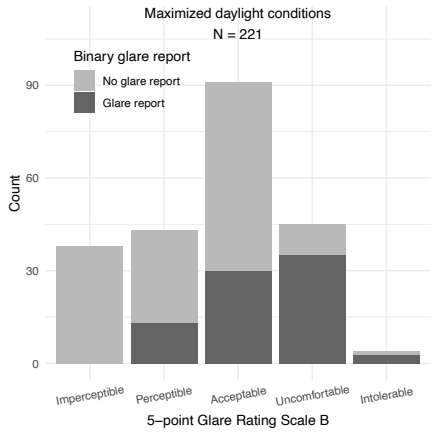


Figure 8.5: Bar plots representing the distributions of the subjective assessments made on the 5-point glare rating scale B during the second discomfort glare evaluation in relation to the binary glare report derived from the OEQ

It can be observed in Figure 8.5 that defining a location for the BCD on the 5-point glare rating scale B would be difficult.

Due to the confusion brought by the Acceptable label, as explained earlier in this section, a large number of subjects picked this cate-

gory. By setting the borderline beyond Acceptable, the visual scenes of the subjects having picked Perceptible and having reported discomfort glare from daylight in the OEQ would be classified as not discomforting. Conversely, by setting the borderline before Acceptable, the visual scenes of the subjects having picked Acceptable and not having reported any discomfort glare from daylight in the OEQ would be classified as discomforting. By setting the borderline at one location or the other, part of the data would be systematically misclassified.

8.2.2 Discussion

In this section, descriptive analyses of the subjective assessments of discomfort glare made by the subjects of the study are conducted. The aim is to evaluate whether the four different subjective assessment methods implemented in the questionnaire of this study agree with each other, and if not, which method does not perform as expected.

Four methods of subjective assessment of discomfort glare, namely a 4-point glare rating scale A, a 5-point scale B, a 4-point scale C, and an OEQ, were applied during the field study to collect subjects' discomfort glare perception.

It should be noted that the order in which these subjective assessment methods were displayed to the subjects was not randomized, but similar for all the subjects. Non-randomizing the subjective assessment methods might have caused some response bias, such as an anchoring effect on the glare scale ratings, with the ratings made on the scales B and C influenced by the ratings made on the scale A. The reasons for not randomizing the subjective assessment methods were that:

- the OEQ needed to come first in order not to draw the subjects' attention to discomfort glare;
- the 4-point scale A had to be the first of the scales so that there was no possibility for the two other scales (B and C) to bias the subjective assessments made on this one, since the subjective assessments made on the 4-point scale A were the

ones used for the investigation of the influence of the socio-environmental context.

Nevertheless, the descriptive analyses of the subjective assessments collected through these four methods showed some interesting results, which could help to better understand how each subjective assessment method can bias subjects' report of their discomfort glare perception.

First, the labels of glare rating scales must be chosen carefully in order not to create semantic bias.

In a first instance, the researchers should ensure that the labels of one glare rating scale refer to only one concept. For instance, it has been hypothesized based on the results in this section that the label "Acceptable" in the 5-point glare rating scale B brought confusion since it referred to the concept of acceptance of glare, whereas the rest of the scale consisted in glare perception. Furthermore, whether the concept that the scale measures should rather be glare perception, discomfort due to glare, or acceptance of glare, is not definite. In this research, it was considered that the aim of the metrics are to predict discomfort due to glare, and therefore, the main glare rating scale (A) had to measure discomfort due to glare.

In a second instance, these labels should require the least interpretation possible from the subjects. As soon as interpretation is needed, e.g., to understand what is meant by Noticeable or Perceptible discomfort glare, different persons might define it differently. The label Noticeable was observed to be the most ticked category in the 4-point scale C, with over 50% of the subjects having chosen that category for the second glare evaluation. Of these subjects, one half did not report any discomfort due to glare in the OEQ, and the other half did. As already mentioned in the literature [Osterhaus et al. 1992], descriptions of the meaning of the labels, for instance using the time during which the discomfort glare stimulus could be tolerated, might help in preventing different interpretations of the labels.

Moreover, transforming subjective assessments of discomfort glare made on a glare rating scale into a binary variable might distort the subjective assessments as originally intended by the subjects. This practice is, however, increasingly used in glare studies, especially with the development of the epidemiological approach to discomfort glare, which requires the discomfort glare metric to "diagnose" between visually discomforting scenes and scenes that do not produce visual discomfort [Rodriguez et al. 2016a; Wienold et al. 2019; Pierson et al. 2018a]. Unless it is shown that the binary transformation of the glare rating scale is in line with some other binary subjective assessment of discomfort glare, it would be recommended to use directly a binary scale for the subjective assessment of discomfort glare. A two-step method can be considered; the first question would determine whether discomfort glare is perceived through a binary scale, and the second question, conditional to the perception of discomfort glare in the first one, would evaluate how much discomfort is caused by glare.

By using a two-steps subjective assessment method with carefully chosen labels including a description of their meaning, it is assumed that there would still be some bias induced by drawing the subject's attention on glare and forcing them to emit an opinion. In this regard, it would be interesting to compare the subjective assessments of discomfort glare collected through this kind of method to those collected via an OEQ.

However, the subjective assessments of discomfort glare derived from the OEQ might also have been biased in different ways.

Firstly, some result suggests that one subject felt that he/she had to report something in the OEQ even though he/she would not have considered this element as really discomforting or unsatisfying.

Secondly, the subjective assessment method based on the OEQ required the investigator to interpret the subjects' answers to this OEQ in order to classify them between No glare report and Glare report. The answer to the OEQ might not have been intended by the subject in the same manner as it was perceived by the investigator.

Lastly, the subject's attention was still drawn on the lighting con-

ditions through the OEQ. The subjects were prompted to evaluate these conditions, although they might not have considered them relevant in the first place. Focusing the OEQ on lighting conditions was however necessary, as in general, subjects tend to only mention one element, the most unsatisfying one. Consequently, it is hypothesized that if the OEQ had been about unsatisfying environmental factors in general, elements related to the lighting conditions would not have been mentioned, as thermal discomfort would have been the predominant issue, especially during the summer months.

All the previously mentioned issues related to subjective assessment methods, as well as other ones that could not be detected, have already been highlighted and described in the literature [Fotios 2018; Fotios 2015; Allana et al. 2019]. For instance, some authors have already underlined the problem that was encountered as the glare rating scale questions were not correctly understood by the Japanese socio-environmental group (Section 6.4). One author warned about the importance of clearly stating what is being evaluated, as well as ensuring that the subject's expressed opinion is meaningful [Fotios 2018]. Although the first recommendation proved not to be correctly implemented in this study, the application of the second recommendation prevented wrong conclusions from being drawn on discomfort glare perception from daylight in the Japanese socio-environmental context.

In conclusion, the aim of the analyses performed in this section is to illustrate, with the collected field study data, to what extent some issues related to subjective assessment methods can distort subjects' discomfort glare perception, to give insights on how the presence of these issues in a dataset can be detected, and to advise on how these issues could be avoided. Further research is highly required on this topic to avoid the spread of biased methods of subjective assessment of discomfort glare, and to propose reliable alternatives.

8.3 Study Type

This section includes amended parts of an open-access study article published at the 29th Session of the CIE [Pierson et al. 2019b].

In Section 6.3, a difference is observed in the performance of the metrics to predict subjects' discomfort glare perception between laboratory and field studies. The metrics seem to be performing better in laboratory studies.

Furthermore, several authors also seem to report that the metrics generally underestimate discomfort glare that is perceived by subjects in real office environments [Mangkuto et al. 2017; Hirning et al. 2014]. This is observed through a difference in the derived cut-off values between field and laboratory studies.

Different cut-off values, corresponding to borderlines between different magnitudes of discomfort glare, are provided with each discomfort glare metric. For instance, cut-off values have been defined for the DGP on its scale ranging from 0 to 1 [Wienold 2009b], and have been recently supported by the results of another laboratory study [Bian et al. 2017]. These cut-off values correspond to the three borderlines of the 4-point glare rating scale C used in this study, as this scale was used to develop the DGP:

- 0.35 is the cut-off value corresponding to the Borderline between Imperceptible and Noticeable glare (BIN)
- 0.40 is the cut-off value corresponding to the Borderline between Noticeable and Disturbing glare (BND)
- 0.45 is the cut-off value corresponding to the Borderline between Disturbing and Intolerable glare (BDI)

Through field studies, researchers have attempted to validate the daylight discomfort glare metrics and their corresponding cut-off values. For instance, the DGP value representative of 50% of field studies subjects disturbed by glare has been evaluated at 0.2 [Hirning et al. 2014] and 0.24 [Mangkuto et al. 2017]. These cut-off values are much lower than the ones originally defined in laboratory studies, which have been recently validated by the results of a

meta-analysis study combining data from seven laboratory studies [Wienold et al. 2019]. Although the cut-off values from the laboratory and field studies were not derived in the same manner, the gap between the field and laboratory cut-off values is considerable as it averages around 0.16 on the DGP scale.

This section aims to assess whether cut-off values derived from laboratory studies are systematically higher than those derived from field studies. If true, this observation would imply that subjects tolerate higher levels of discomfort glare in office-like laboratory cells than in real offices.

For this purpose, the cut-off values of the five daylight discomfort glare metrics, derived for three borderlines (BIN, BND, and BDI), and using data from both laboratory and field studies are compared.

The two laboratory studies from which the datasets are analyzed in this section have been chosen for their similarities with this field study. They share a similar protocol, described for each study respectively in [Moosmann et al. 2012] and [Sarey Khanie et al. 2017], similar visual scenes with the subject seating at an office next to a window (Figure 8.6), and a similar glare rating scale, the 4-point scale C. The two laboratory studies were conducted in the same office-like laboratory cell in Freiburg (Germany).



(a) Laboratory study [Moosmann et al. 2012] (b) Laboratory study [Sarey Khanie et al. 2017] (c) Field study in the Swiss context

Figure 8.6: Typical visual scenes assessed by the subjects in the two laboratory studies, and in the field study

Regarding the field study, only the data collected in the Swiss so-

cio-environmental context is used since the subjective assessments of discomfort glare made on the 4-point glare rating scale C are required. Furthermore, the third data cleansing rule controlling for the error in vertical illuminance of the luminance map is modified to be aligned with the two laboratory studies. Data points are excluded for errors less than -25% or greater than $+25\%$.

After data cleansing, the merged laboratory datasets and the field dataset contained respectively 140 and 94 data points (Table 8.2). Each data point consists of a subjective assessment of discomfort glare made on the 4-point glare rating scale C and the discomfort glare metric values corresponding to the assessed visual scene.

Dataset	N	Discomfort on 4-point scale C			
		Imperceptible	Noticeable	Disturbing	Intolerable
Laboratory	140	65	38	33	4
Field	94	21	46	23	4

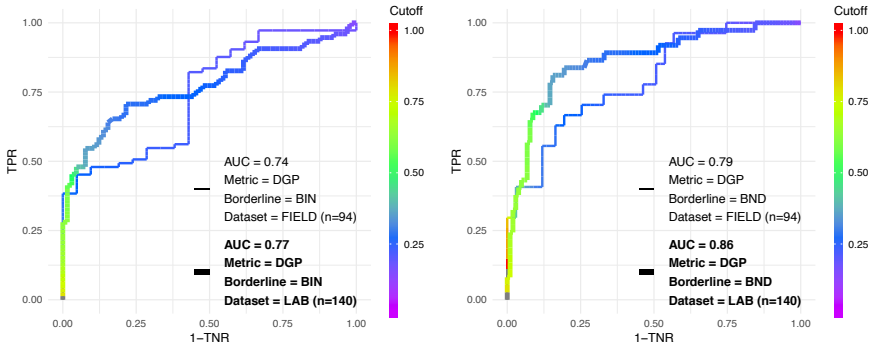
Table 8.2: Information on the datasets used for the analysis of the study type (Section 8.3)

In Table 8.2, it can be observed that the distributions of the ratings on the 4-point scale are not exactly similar. More specifically, there were many more Imperceptible ratings during the laboratory study than during the field study.

8.3.1 Analyses and Results

Cut-off values are derived separately for the laboratory and field datasets, for the three borderlines of the 4-point scale C, and for the five daylight discomfort glare metrics. To derive these values, ROC curve analyses are first performed. A ROC curve is indeed a plot of the TPR and TNR of a range of cut-off values of the metric for a specific borderline. The ROC curves based on the DGP for the BIN and BND are shown in Figure 8.7. All ROC curves are available in Appendix G.

From the ROC curves for the BIN and BND displayed in Figure 8.7, it can be observed that the metrics perform slightly better in discriminating the visual scenes from the laboratory studies according to the subjects' subjective assessments than those from the field



(a) ROC curve for BIN

(b) ROC curve for BND

Figure 8.7: ROC curves from the analyses of the performance of the DGP to predict the first BIN and second BND binary transformations of the ratings on the 4-point glare rating scale C for the field study and the laboratory study groups

study. The AUC of the ROC curves derived from the field data are indeed a bit lower than those derived from the laboratory data. This observation supports the difference in the Spearman's rank correlation coefficients found in Section 6.3.

Unfortunately, the ROC curves for the BDI cannot be trusted and the corresponding cut-off values cannot be derived. The curves are based on too low a number of data points in one of the two subjective assessment categories (Figure 8.8). There were indeed only 4 Intolerable ratings out of 140 subjective assessments in the laboratory studies, and 4 Intolerable ratings out of 94 subjective assessments in the field study.

From these ROC curves, several methods can be used to define the best cut-off value, namely the one that produces the discrimination of the visual scenes that best matches the discrimination made by the binary subjective assessments. Three of these methods are applied to derive the three best cut-off values, and the mean of these three best cut-off value is used for the comparison. The three methods to derive the best cut-off value are:

- the one that minimizes the distance from the ROC curve to the upper left corner of the graph,

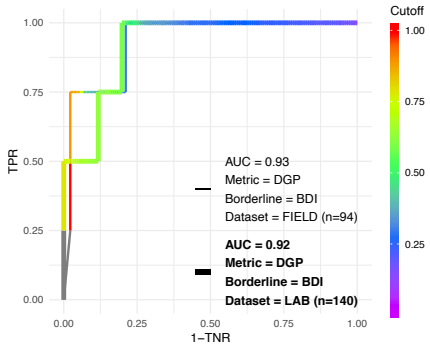


Figure 8.8: ROC curves from the analyses of the performance of the DGP to predict the third BDI binary transformation of the ratings on the 4-point glare rating scale C for the field study and the laboratory study groups

- the one that maximizes the Youden index (Equation 8.1),
- and the one that maximizes a square fitting under the curve.

The methods are described in detail in [Wienold et al. 2019].

$$Youden\ Index = TPR + TNR - 1 \tag{8.1}$$

By applying this procedure, the best cut-off value is derived for each dataset (laboratory and field), for each borderline (BIN, BND, and BDI), and for each daylight discomfort glare metric (DGP, CGI, DGI, E_v, and L_{mean}). These cut-off values are displayed in Table 8.3.

As previously mentioned, the cut-off values derived for the BDI are given for information but should not be trusted due to the very small amount of data in the highest category of the glare rating scale.

The comparison of the best cut-off values for each study type presented in Table 8.3 shows that the cut-off values derived from the laboratory data are larger than those derived from the field data. Furthermore, the gap between the cut-off values is so large in some cases that, for instance, the five cut-off values of the BND derived from the field data are smaller than those of the BIN derived from the laboratory data.

Metric	Borderline	Cut-off values	
		Laboratory study	Field study
DGP	BIN	0.28	0.23
CGI		27	19
DGI		17	15
E_v		1903	836
L_{mean}		681	359
DGP	BND	0.36	0.26
CGI		29	26
DGI		19	16
E_v		2949	1064
L_{mean}		942	520
DGP	BDI	0.57	0.29
CGI		40	30
DGI		25	20
E_v		6004	6938
L_{mean}		1412	588

Table 8.3: Mean values of the results of three methods to derive the best cut-off values from the ROC curve analyses of the performance of each of the five discomfort glare metrics to predict the three (BIN, BND, and BDI) binary transformations of the ratings on the 4-point glare rating scale C for the field study and the laboratory study groups

This result can also be observed from the color scale of the ROC in Figure 8.7. The difference of color between the two curves for an equivalent point, i.e. a point where the curves cross each other, implies that the cut-off values at that point are different. More specifically, the cut-off values derived from the laboratory data seem systematically higher than the cut-off values derived from the field data.

8.3.2 Discussion

As it was first detected in Section 6.3, the results suggest that daylight discomfort glare metrics perform better in laboratory studies than in field studies. This performance difference is potentially due in part to the noise inherent to field studies as extraneous variables, such as the air temperature (Section 7.4), could have a confounding effect, whereas these extraneous variables are better controlled in laboratory studies.

Besides a tendency towards a lower performance of the metrics in field studies, the results of the ROC curve analyses seem to support what has already been highlighted in the literature: discomfort glare is reported at lower stimulus magnitudes in real offices than in office-like laboratory cells. Several hypotheses that could explain this difference are detailed below, although this list might not be exhaustive.

The first hypothesis is that the difference in cut-off values can be partly explained by an anchor bias. When using an adjustment method to evaluate discomfort glare perception, some authors pointed out that "*the final setting is influenced by the initial stimulus*" [Kent et al. 2017b]. The issue of an initial stimulus influencing following evaluations could also occur when using category rating scales. Different initial lighting conditions could lead to different subjective assessments of discomfort glare made for following visual scenes, with these assessments being potentially biased towards the initial conditions.

Since in the field study, the subjects were first asked to do an evaluation in the original lighting conditions, and these conditions were on average relatively dim and usually comfortable, the subjects' second subjective assessment might have been biased. As the subjects noticed an increase in the brightness of the scene, they might have been tempted to somehow adapt their rating towards a higher category, namely a more discomforting one, to show that they had noticed the change, although the situation was not really discomforting but just brighter.

A second hypothesis that could explain the gap in the cut-off values is the difference in the stimuli ranges and in the distributions of these stimuli between field and laboratory studies.

Several mentions can be found in the literature where it is reported that exposure conditions in laboratory tests of indoor comfort studies are often higher than the ones experienced in most buildings [Torresin et al. 2018; Lamb et al. 2016; Chinazzo et al. 2018]. This trend is observable in the field of daylighting: in Table 8.4, the vertical illuminance levels reported for different laboratory and field

studies are presented.

Type	Study	Mean E_v	Median E_v	Maximum E_v
Field	[Konis 2014]	NA	905	1289
	[Hirning et al. 2014]	444	NA	2354
	[Mangkuto et al. 2017]	905	NA	2380
Laboratory	[Wienold 2009a]	3493	3010	11298
	[Konstantzos et al. 2016]	2896	NA	5940
	[Rodriguez et al. 2016b]	2632	NA	NA

Table 8.4: Descriptive statistics (mean, median, and maximum) of the vertical illuminance at eye level to which subjects are usually exposed in field or laboratory studies

In Table 8.4, the comparison shows that the range of vertical illuminance experienced in real office buildings is generally lower than the range of vertical illuminance to which subjects are exposed in laboratory settings. This difference is most probably due to the fact that, in real buildings, uncomfortable conditions, such as glare, are typically avoided, whereas, in laboratory studies, researchers aim at creating a full bandwidth of situations, including uncomfortable ones.

Moreover, as shown in Figure 8.9, the distributions of the vertical illuminance for the laboratory data and field data are relatively different, and not following a normal distribution. The difference in the stimuli ranges and in the distributions of these stimuli between field and laboratory studies could have an impact on the ROC curve analysis, and in turn on the derived cut-off values.

Another hypothesis to explain the difference in cut-off values is the difference in experience in the lighting conditions of the scene when a subject assesses discomfort glare in her/his own office or in a laboratory cell.

The subjects of each study were asked to make a point-in-time assessment of the perceived discomfort glare at the present moment when the study took place. However, in the case of the field study, the subjects might, unconsciously, have taken into account past situations at their desk while doing the assessment. In the laboratory study, this experience effect would be different since the subjects saw the laboratory cell for the first time when they performed the

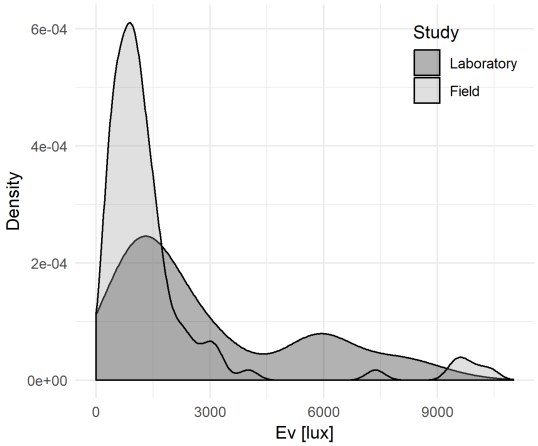


Figure 8.9: Density plot reprensenting the distribution of the E_v experienced by the subjects during the laboratory and field studies

study, and they might have compared the lighting situation to their usual workplace.

Moreover, evidence from the literature suggests that subjects have a tendency to recall previously encountered stimuli as lower than they really were [Fotios 2018; LeBoeuf et al. 2006]. subjects of the field study could have compared the present visual scene, namely the one they were asked to assess, to past situations, which they recall less discomforting. They would therefore have made a relative assessment based on this comparison, which would have been more severe than if there had been no experience at the desk and no anchors to relate to. Furthermore, exacerbation due to a prolonged exposure or effects of a frequent stressor can play a role in the subjective assessment made in a field study [Torresin et al. 2018].

Somewhat related to the previous hypothesis, a fourth hypothesis would be that expectations towards a familiar environment play a role in the subjective assessment of discomfort glare.

The subjects having to assess a familiar visual scene, i.e., the subjects of the field study, might be more critical, as they have higher expectations for a scene that they experience every day. Therefore, the field study subjects might be more demanding since they are

directly affected by that visual scene in their everyday life. This is not the case in a laboratory environment, since the subjects know they will not have to work under these conditions in the future. Furthermore, the subjects in a laboratory study volunteer to take part in a study, whereas subjects of a field study might feel a bit more forced to do it. The difference in their free will to volunteer could influence their attitude, as a subject who has deliberately chosen to take part in a study might be in a more positive mindset. Both the attitude and the expectations could influence a subjective assessment [Lamb et al. 2016].

The last hypothesis is that the different study contexts, even though they are aimed to be similar, might trigger different behaviors or simply be perceived differently by the subjects, which causes them to make different subjective assessments. For instance, a subject could feel different, e.g., more relaxed or curious, in a laboratory environment than in her/his usual working environment. Moreover, environmental factors, such as the view through the window, might be more appealing or dissatisfactory in an unknown environment than the view to which a subject is accustomed.

Furthermore, confounding variables related to the physical environment, such as temperature or air quality, might also play a role, as these are not always controlled in field studies. Confounding variables could make the subject less sensitive to discomfort glare in a laboratory environment than in her/his usual work environment.

8.4 Conclusion

In this chapter, two potential experimental biases of discomfort glare studies were investigated in a bit more detail, namely the **subjective assessment method** and the **study type**, i.e., field or laboratory study. These two potential experimental biases are both found to influence in some ways the results of a study. Although they would have no impact outside of a study context, these experimental biases are still worth investigating since, by influencing the results of discomfort glare studies, they play a role on how discomfort glare is understood and managed.

It appears that this type of factor has only been studied for a short amount of time in the field of discomfort glare research, compared to the factors assumed to influence discomfort glare perception. More studies are now appearing that demonstrate biases related to study factors in existing discomfort glare studies, or highlight potential ones [Fotios 2015; Fotios 2018; Fotios et al. 2010; Fotios et al. 2011; Kent et al. 2017c; Kent et al. 2017b; Kent et al. 2018c; Kent et al. 2019; Logadóttir et al. 2011; Allana et al. 2019]. The results of these studies obviously question the foundations on which discomfort glare research is built. It is therefore imperative that these experimental biases are further studied and widely communicated. In addition, solutions to prevent these experimental biases from influencing the outcomes of a study should be suggested and validated. These solutions would ensure that the results of future discomfort glare studies can be trusted, and would unify the way in which discomfort glare is studied so that results can be compared.

Regarding the methods for the subjective assessment of discomfort glare, and especially the glare rating scales, these methods have been observed to distort in some ways the subject's discomfort glare perception, and thus prevent the capture and analysis of faithful perceptions. Insights have been suggested based on the results of this study to avoid distorting the data and drawing wrong conclusions. Recommendations to existing literature have also been given in order to develop more reliable discomfort glare studies [CIE 2014; Fotios 2018; Fotios 2015; Uttley 2019; Allana et al. 2019].

In any case, further research is required to define a validated glare rating scale. Work from Kent et al. goes into that direction, with the development of the BEARS scale of subjective glare evaluation, although the robustness of that scale to evaluate the sensation of discomfort due to glare still needs to be tested and validated [Kent et al. 2018a]. In this regard, a study investigating the interpretation of the labels of various glare rating scales would be very useful in order to select the least biased scale, which should then be recommended by the CIE. For instance, in the field of thermal comfort, a thermal sensation scale has been defined and validated, and is recommended in [ASHRAE 2013]. Moreover, other methods of subjective assessment of discomfort glare, such as the drawing-based question, should be developed to compensate for current issues in glare rating scales.

On another note, some results in this chapter also suggest that the study type, i.e., whether a field or a laboratory study is conducted, could have an influence on the stimulus magnitude at which discomfort glare is reported. Although this observation had already been highlighted previously in the literature, the results of this study allow to quantify the gap between cut-off values derived from field and laboratory studies. Several hypotheses are provided to explain this gap, but further research is required to identify which one is the most probable. For instance, field studies could be conducted in offices building where desk occupancy is flexible, i.e., flex desk, to attenuate bias related to expectations or experience at the subjects' own desks. Laboratory studies with a range of stimuli similar to those that are found in the field could also be conducted to investigate the bias related to different stimuli distributions. Lastly, the subject's stress level while taking part in a study and her/his satisfaction at work should be recorded systematically and analyzed simultaneously to detect any confounding effect on the subjective assessment of discomfort glare.

Finally, other potential experimental biases, which are related to data analysis rather than data collection, could affect the results of discomfort glare studies and are worth mentioning.

A first example of such factors is the lighting measurement method used in the discomfort glare study. In this regard, HDR photography is increasingly applied, since it allows to measure all the relevant lighting quantities for the study of discomfort glare in the entire FOV at once. However, the calibration process to produce luminance maps with commercially available equipment, more commonly used than luminance cameras, is tedious and error-prone. This is the reason why a comprehensive tutorial of the HDR photography step-by-step calibration process for applications in daylighting has been defined in the scope of this research [Pierson et al. 2019a]. This tutorial insists on the need to collect enough lighting measurements to calibrate the luminance map, but also to check its validity. The majority of the published studies relying on "manually" calibrated HDR images do not perform this validity check, although it has been observed that errors of around 75% in E_v could occur even when the step-by-step calibration process is rigorously applied [Pierson et al. 2019a]. In the future, similar tutorials should be established for applications in artificial lighting, road lighting, and color studies. Moreover, a quality criterion should be defined so that a validity check is compulsory when using manually calibrated HDR images, ensuring that the results of discomfort glare studies are not based on incorrect measurements.

Furthermore, the glare source detection method in evalglare [Wienold et al. 2004] is another study factor that could affect the results of discomfort glare studies. The glare source detection method consists of the rule and parameters that are used by the evalglare algorithm to detect, in a 180° luminance map, the pixels that should be treated as glare sources, so that the discomfort glare metrics can be calculated based on these glare sources. In the framework of this research, different glare source detection methods available in evalglare have been investigated [Pierson et al. 2018a], since these methods influence the discomfort glare metric values, and therefore affect the accuracy of discomfort glare evaluation performed by the metrics. The results of the investigation show that the choice of a glare source detection method could lead to very different results, with some visual scenes that could be classified as either

Imperceptible glare or Uncomfortable glare depending on the glare source detection method used in evalglare. Although more research is required to define which glare source detection method best reproduces that of the subject, the results of the investigation offer guidelines to choose the method that is the most appropriate for the situation, but most importantly, they ensure that the choice is made taking into account the impacts it may have on the results of the study.

These two investigations have been published in scientific journals, and are available respectively in appendices I [Pierson et al. 2018a] and J (with permission of the Illuminating Engineering Society) [Pierson et al. 2018b].

In conclusion, it is highly recommended that potential experimental biases are thoroughly studied in the future, so that their influence on the results is known. The design of future discomfort glare studies can then be defined in accordance, to avoid their effect on the results. In order to better understand and evaluate discomfort glare perception in the future, it is essential that discomfort glare research produces reliable results.

Chapter 9

Conclusion

9.1 Main Outcomes

This research aims at providing solutions to improve the prediction of discomfort glare perception from daylight in office buildings. More specifically, the influence of the socio-environmental context of the subject on discomfort glare perception from daylight is investigated in order to answer the main research question. As defined in Subsection 2.2.3 (p.114), the socio-environmental context of the subject refers to the climate and habitat, including indoors and outdoors, to which a subject has been acclimatized, her/his behavior towards these elements, and her/his expectations about them.

In this context, two additional research questions are defined for exploratory research purposes. These two additional questions target the potential influence of additional factors related to the subject and to the context on discomfort glare perception from daylight, as well as the potential effect of experimental biases on the results of discomfort glare studies.

For these purposes, a cross-sectional, between-subjects, field study was conducted in real office buildings located in four socio-environmental contexts, namely Chile, Belgium, Japan, and Switzerland. Two discomfort glare evaluations, one in the original lighting conditions and one in maximized daylight conditions, were collected at the office desk of each subject, together with the evaluation of 13 additional factors. The protocol of the study was defined in such a way that potential experimental biases related to glare rating scales could also be investigated at a later stage. The discomfort glare evaluation consisted in a subjective assessment of discomfort glare in the visual scene, directly followed by lighting measurements of the scene through HDR photography. In total, 802 discomfort glare evaluations made by 401 subjects were collected.

The raw data was processed to derive useful information for the analyses, and cleansed according to specific rules to ensure data quality. Depending on the subjective assessment method considered, i.e., the 4-point glare rating scale A or the binary glare report, two datasets were derived containing respectively 234 (Table 4.5) and 232 discomfort glare evaluations (Table 4.6).

In the first place, the **main research question** of the thesis, which is to determine whether the socio-environmental context of a subject influences her/his discomfort glare perception from daylight in office buildings, was addressed in Chapter 6. The nature of this research question was **explanatory research**, since it principally consisted of testing the hypothesis stating that subjects acclimatized to different socio-environmental contexts perceive differently discomfort glare from daylight. The analyses of the collected data performed in Chapter 6 produced the following results.

No statistically significant differences in the subjective assessments of discomfort glare from daylight could be observed between subjects from the Chilean, Belgian, Japanese, and Swiss contexts. The results suggest that the five daylight discomfort glare metrics were acceptable models to discriminate between visual scenes that were reported as discomforting and not discomforting by the subjects of the four contexts. Moreover, there was no evidence of a consistent and/or significant difference in the sensitivity to discomfort glare from daylight between the subjects from the four contexts.

Based on these results, it is inferred that:

> This study does not support an influence of the socio-environmental context of the subject on her/his discomfort glare perception from daylight in office buildings.

By including the outcome of this study in Table 2.3, the indicator of the likelihood of the influence of the socio-environmental context on discomfort glare perception changes of category, going from a somewhat likely influence to an inconclusive influence. Further research, not restricted by the limitations of this study, is therefore required to validate this finding.

Then, the **first additional research question** of the thesis, which is to determine whether additional factor(s), among a list of 13 preselected factors, has/ve a probable influence on the subject's discomfort glare perception from daylight in office buildings, was

addressed in Chapter 7. From the list of 13 additional factors, the influence of five of them could be investigated in the framework of this research. These five additional factors are chronotype, self-assessed glare sensitivity, iris pigmentation, the attractiveness of the view through the window, and the air temperature of the room.

The nature of this additional research question was **exploratory research**, since it sought to create hypotheses regarding the influences of these five factors on discomfort glare perception from daylight, rather than demonstrate them. The analyses of the collected data performed in Chapter 7 produced the following results.

The data analyzed suggest a probable influence of three factors on the subjective assessment of discomfort glare from daylight, namely self-assessed glare sensitivity, the attractiveness of the view through the window, and the air temperature of the room. Although the influences of these factors cannot be proven in the framework of this study, the results led to the development of hypotheses in order to guide the development of future studies.

Firstly, a statistically significant relationship between the self-assessed glare sensitivity of the subject and her/his subjective assessment of discomfort glare from daylight was detected regardless of the socio-environmental context of the subject. A discomfort glare prediction model including the glare sensitivity would improve the prediction of perceived discomfort glare. Based on the collected data, it is expected that the more a subject assesses her/himself as sensitive to glare, the lower is the discomfort glare metric value at which he/she reports discomfort glare from daylight.

Based on these results, the first hypothesis indicates that:

> This study suggests that the glare sensitivity of a subject has a probable influence on her/his discomfort glare perception from daylight in office buildings. More specifically, self-assessed glare sensitive subjects would report discomfort glare from daylight at lower daylight discomfort glare metric values.

Secondly, a statistically significant relationship between the attractiveness of the view through the window assessed by a subject and her/his subjective assessment of discomfort glare from daylight was detected regardless of the socio-environmental context of the subject. Based on the collected data and former research on this topic [Tuaycharoen et al. 2005; Tuaycharoen et al. 2007], it is expected that the more attractive the subject rates the view through the window, the higher the discomfort glare metric value at which he/she reports discomfort glare from daylight.

Based on these results, the second hypothesis indicates that:

> This study suggests that the attractiveness of the view through the window assessed by a subject has a probable influence on her/his discomfort glare perception from daylight in office buildings. More specifically, a view assessed as more attractive by the subject would make her/him report discomfort glare from daylight at higher daylight discomfort glare metric values.

Thirdly, a statistically significant relationship between the air temperature and a subject's subjective assessment of discomfort glare from daylight was detected in the Swiss socio-environmental context. The analyses of this relationship based on the collected data suggest that the higher the air temperature, the more the subject will report discomfort glare from daylight in that context.

Based on these results, the third hypothesis indicates that:

> This study suggests that the air temperature has a probable influence on a subject's discomfort glare perception from daylight in office buildings for subjects acclimatized to the Swiss socio-environmental context. More specifically, discomfort glare from daylight would be reported more often at higher air temperatures by a Swiss subject.

Finally, the **second additional research question** of the thesis, which is to determine whether experimental bias(es), among a list of five potential biases, has/ve a probable influence on the results of studies on discomfort glare perception, was addressed in Chapter 8. From the list of five potential experimental biases, the effects of two of them could be investigated in the framework of this research. These two potential experimental biases are the glare rating scales and the study type.

The nature of this additional research question was **exploratory research**, since it sought to create hypotheses regarding the effects of these two experimental biases on the results of studies on discomfort glare perception, rather than demonstrate them. The analyses of the collected data performed in Chapter 7 produced the following results.

The data analyzed suggested probable effects of both experimental biases on the results of studies on discomfort glare perception. Although the effects of these experimental biases cannot be proven in the framework of this study, the results led to the development of hypotheses in order to guide the development of future studies.

On the one hand, the results showed evidence that several methods of subjective assessment of discomfort glare, among which three glare rating scales, affected the expression of the subject's discomfort glare perception and/or distorted the interpretation of her/his subjective assessment. These probable biases seemed to be related to the references to different concepts in a single scale, to the interpretations of the labels of the scales, to the imbalance in the scales categories, to the incitement to issue an opinion, or to the posterior transformation of category rating scales into binary variables.

Based on these results, the fourth hypothesis indicates that:

> This study suggests that several subjective assessment methods have a probable influence on the results of studies on discomfort glare perception. More specifically, the subject's discomfort glare perception would not be faithfully captured through these subjective assessment methods, hence biasing the results of the studies implementing them.

On the other hand, the results also showed evidence that the study type, namely a field or a laboratory study, affected the cut-off values derived as borderlines between different magnitudes of discomfort glare, and, to a lesser extent, the performances of the discomfort glare metrics. The results of studies on discomfort glare seem to vary depending on the study type.

Based on these results, the fifth hypothesis indicates that:

> This study suggests that the study type has a probable influence on the results of studies on discomfort glare perception. More specifically, discomfort glare would be reported at lower metrics values in field studies than in laboratory studies.

Further research, dedicated to each of these probable additional factors and experimental biases and not restricted by the limitations of this study, is required to test these hypotheses and potentially validate the influence of other factors on discomfort glare perception from daylight in office buildings.

To sum up, this study brings forward several elements to improve the prediction of discomfort glare perception from daylight in office buildings.

Based on the main outcomes previously detailed, the socio-environmental context of the subject seems not to be a relevant variable to improve the prediction of discomfort glare perception from daylight

in office buildings. On the other hand, the prediction of discomfort glare perception from daylight in office buildings could be improved by considering factors related to the subject, and especially the glare sensitivity, or environmental factors, such as the attractiveness of the view through the window and the air temperature.

Lastly, the main outcomes of the study also suggest that the prediction of discomfort glare perception from daylight in office buildings could be improved by ensuring that the development of daylight discomfort glare metrics is based on studies designed and carried out in such a way as to produce the least biased and the most reliable outcomes.

9.2 Limitations

The obtained results are subject to several limitations, detailed below.

Firstly, the data for the Chilean socio-environmental context was collected in three cities with different latitudes, and therefore different climates and daylight conditions. Since the samples collected in each city were not large enough to be studied individually, these samples were merged into one unique dataset. Therefore, data from the two cities further south in Chile could have somehow mitigated the data from Antofagasta City, which could have been particularly relevant in the comparison of different socio-environmental contexts in view of its high annual sum of GHI.

Secondly, it must be noted that none of the four studied socio-environmental contexts endure an extreme variation in terms of daylight hours throughout the year. The difference in daylight hours in these four contexts ranges from 4h 51m in Tokyo to 9h 26m in Punta Arenas, and the minimum numbers of daylight hours per day that some of the subjects of this study experience in one year is 7h 32m. Therefore, the findings should be interpreted carefully when applied to socio-environmental contexts with more extreme variation in terms of daylight hours, such as Reykjavik, which has a difference in daylight hours of 17h with a minimum of around 4h of daylight a day in winter. In such extreme contexts, the "*shortage of sunlight creates a general positive attitude to it that may influence evaluation of the glare from windows*" [Matusiak 2013].

Thirdly, the time allocated to adapt to the lighting conditions in which daylight is maximized was relatively limited. Since the subject adapted to these modified lighting conditions while answering the part of the questionnaire in which general information was gathered, an average adaptation time of around five minutes was provided before the subject had to make her/his subjective assessment of discomfort glare from daylight. The exact time required for the subject's eyes to adapt to a new visual scene is still unknown. In the literature, there is evidence of the subjects' discomfort glare perception varying in the first 30 seconds of exposure to the light

stimulus [Iwata et al. 1990; Sivak et al. 1997], but stabilized after a period of exposure of 8 minutes [Mochizuki et al. 1998]. Another study shows, however, that there is no difference between the subjective assessments of discomfort glare made at the beginning and at the end of a one-hour session for a constant stimulus [Geerdinck 2012]. Consequently, recommendations regarding the minimum adaptation time required before a subjective assessment of discomfort glare are needed.

Fourthly, for 84% of the subjects, the lighting conditions were modified before they made the second discomfort glare evaluation. Indeed, it was required to open the shading devices and/or turn off the electric lighting at some point in order to maximize the potential for daylight discomfort glare occurrence. The modification of the lighting conditions, which involved the testing of two visual scenes for each subject (before and after the modification) as explained in Subsection 4.1.9, was necessary so that there were visually discomforting scenes in the dataset. However, modifying the lighting conditions between the two glare evaluations without randomization (the potentially more discomforting scene was always the second one, when the lighting conditions had been changed) most probably biased the subjects' subjective assessments of discomfort glare. It would therefore be useful to repeat this study in real office buildings where daylight discomfort glare occurs naturally, so that there is no need to modify the lighting conditions in order to collect visually discomforting cases for the statistical analyses.

Fifthly, the recommended method for evaluating some of the other factors, such as the MCTQ [Roenneberg et al. 2003] for the chronotype, the PANAS [Watson et al. 1988] for the emotional state, or the conventional scales [ASHRAE 2013; ISO 2019] for the thermal comfort, were not used in this study, mainly because of time constraints. Instead, informal but straightforward methods consisting of one or two questions with rating scales, as shown in Subsection 4.1.6, were implemented in the questionnaire. These less formal methods could have hindered a proper evaluation of the factors, which in turn could have biased the results.

Furthermore, the two main methods to collect subjective assessments of discomfort glare, namely the binary glare report derived from the OEQ and the 4-point glare rating scale A, have also never been validated or recommended in the past. Section 8.2 indicated that these subjective assessment methods could have biased the subjects' expression of their discomfort glare perception, either through the imbalance in the categories of the glare rating scale or through the incitement to issue an opinion. The results of the study should therefore be interpreted in consequence. Moreover, it is highly needed that a subjective assessment method for discomfort glare is validated in the future, and that the research questions of this study are reinvestigated using that validated method and the conventional methods for evaluating the additional factors.

Finally, the visual scenes investigated during the field study were carefully selected to maximize the occurrence of saturation glare from daylight. Selection criteria and cleansing rules were applied so that the scenes were comparable in terms of type of discomfort glare, as daylight discomfort glare metrics are assumed not to perform similarly for saturation and contrast glare. Since daylight is more often associated with saturation glare, the visual scenes were selected in order to reduce the potential for contrast glare from daylight, and to increase that for saturation glare. The findings of this study might be different under contrast glare from daylight. Furthermore, some authors argue that subjects' discomfort glare perception is different depending on whether the glare source is from electric lighting or from daylighting [Borisuit et al. 2015; Laurentin et al. 2000]. For this reason, extending the findings of this study to discomfort glare from electric light seems unsound.

9.3 Implications

With Regard to Research

First of all, the findings of this research expand the knowledge on discomfort glare perception from daylight. Moreover, they raise awareness regarding some methods applied to study discomfort glare perception that produce questionable results, and the need to establish reliable and commonly accepted methods.

Through the main research question, this study provides evidence that there might be no differences in discomfort glare perception from daylight between subjects of different socio-environmental contexts. Upon validation by further studies, this outcome would imply that there would be no acclimatization process affecting discomfort glare perception from daylight. Consequently, the results of discomfort glare research conducted around the world could be globalized and compared without the risk of bias related to the population tested. Furthermore, research efforts could focus on improving one general approach to predict discomfort glare perception from daylight, rather than each region developing its own discomfort glare metric.

Through the additional research questions, the glare sensitivity is hypothesized to influence discomfort glare perception from daylight. Although further studies are required to validate this finding, the influence of a factor directly related to the subject would demonstrate that physiological and psychological factors play a role in the mechanism of discomfort glare perception. Furthermore, the study of the self-assessed glare sensitivity factor could help in determining which physiological and psychological factors influence discomfort glare perception. By determining the physiological factors playing a role, the mechanism of discomfort glare could be better understood, and discomfort glare perception potentially better predicted. Instead of relying on metrics only based on subjective assessments of discomfort glare, a new metric could be developed that would include physiological mechanisms of discomfort glare.

Moreover, two environmental factors, i.e., the view through the

window and the air temperature, are also hypothesized to influence discomfort glare perception from daylight. The influence of these factors demonstrates the importance of controlling for environmental factors, or at least monitoring them correctly, in studies looking at discomfort glare perception from daylight. More generally, the probable influence of these two environmental factors shows that indoor environments are multi-sensory environments in which factors interact. These factors can hardly be studied in isolation in field studies, and maybe they should not be. In the end, what matters when working on improving the IEQ is the combined effect of these environmental factors on the occupants' perception.

Finally, the findings regarding the experimental biases suggest that some existing studies on discomfort glare perception could have been affected by these experimental biases, and that the results of these studies would need to be checked.

Nowadays, there exist a large variety of ways to define the protocol of a study on discomfort glare perception, such as different subjective assessment methods or different lighting measurement methods. Each of these methods becomes an experimental bias as soon as it affects the results of the study. Hence the necessity to validate the chosen method, or to choose a validated method, to ensure the reliability of the results. In the literature, few if any of these methods have been validated. On the contrary, recent studies have shown that some of these methods are not valid, and introduce biases in the results [Kent et al. 2017b; Kent et al. 2018c; Kent et al. 2019; Fotios 2018].

By suggesting how several research methods could influence the results of a study, this study raises awareness towards the importance of making conscious choices regarding the definition of the protocol of the study, i.e., in full awareness of how the choices could influence the results, and of being able to verify the reliability of the results. More specifically, the outcomes of the study suggest the following research steps in order to avoid some experimental biases:

- a pilot study should be conducted to test the applicability of the protocol and the understanding of the questionnaire

- several randomized subjective assessment methods could be used to ensure the consistency and the correct interpretation of the answers, although more research is required on this topic
- two additional and independent lighting measurements should be collected together with the HDR image to check its validity
- the glare source detection method should be selected appropriately in regards of the lighting conditions in the visual scenes of the study
- potential confounding variables, such as baseline characteristics and environmental factors, should be monitored and controlled for in the statistical analyses

If any of these steps are missed, the data could be biased, hence leading to distorted results and misleading conclusions.

In conclusion, this research provides a non-exhaustive list of the elements of a protocol that can become experimental biases and affect the results of a study. Moreover, the study gives a few examples of how some methods, which are currently used to study discomfort glare perception in the literature, can easily lead the researchers to draw wrong conclusions.

With Regard to Practice

In terms of practice, determining that there is no difference in discomfort glare perception from daylight between different socio-environmental contexts would be a positive outcome. This finding would mean that the same daylight discomfort glare metric could be used all over the world. As of today, the DGP seems to be the most robust metric for daylight.

As mentioned, the hypothesized influence of the glare sensitivity is meaningful for research since this finding supports the development of future studies on physiological and psychological factors influencing discomfort glare perception from daylight, and therefore pushes for a better understanding of its mechanism. In practice, adding a factor related to the subject in the method to predict daylight discomfort glare could prove meaningful in some applications, but

only if this factor is easily assessed. The self-assessed glare sensitivity could be assessed by the subject in one easy question, and help explain a small part of the variation between subjects' discomfort glare perception. Although this factor would not be relevant to the assessment of the visual discomfort in a building during the design phase, as there is no way of assessing the glare sensitivity of the future occupants, this factor, as well as other easily assessed factors related to the subject, could be useful in applications such as smart sensor-based lighting and shading control systems for IEQ, allowing the user to improve the efficiency of the system by personalizing it to her/his characteristics.

Furthermore, the hypothesized influence of two environmental factors on discomfort glare perception from daylight would encourage the development of more integrative control systems for IEQ. In light of the findings of this research, as well as other recent research results [Chinazzo 2019; Torresin et al. 2018], the IEQ, but also the energy consumption of buildings, can be optimized by considering the combined effect of environmental factors rather than each of them individually. Integrative control systems could indeed benefit from the mitigation effects that some environmental factors can have on others, such as the effect that air temperature might have on discomfort glare perception from daylight.

On another note, since it is hypothesized from the results of this research that the view through the window can influence the subject's tolerance towards discomfort glare perception from daylight, there might be a greater interest in developing glare protection solutions that allow the buildings' occupants to maintain a view to the outside, especially if the view is attractive.

9.4 Future Work

In the end, the aim of this research was to improve the prediction of discomfort glare perception from daylight in office buildings. The study produced interesting results in relation to some factors assumed to play a role in discomfort glare perception, but also in relation to the reliability of some methods of studying discomfort glare perception. More research is still necessary to validate the outcomes of this study, as well as to further develop the understanding of discomfort glare perception, and to improve the quality of research in that field. Four relevant perspectives based on the results of the study are used to draw priorities and recommendations for future research.

Influence of Study Factors and Reliable Study Design

In a first step, future studies should aim for the validation of reliable methods to study discomfort glare, and for the development of a unified framework regarding the main elements of the protocols of discomfort glare studies. This first step is primordial to ensure that the results of future studies are reliable.

This study has produced a non-exhaustive list of the elements of the study protocol that could have affected the results presented above, if these elements had not been implemented carefully, by considering different methods for instance, and thoroughly checked. These elements include, but are not limited to, the study type (field or laboratory), the questionnaire, the subjective assessment method, the lighting measurement method, the data processing through evalglare, and the control of extraneous variables. Furthermore, this study shows how some of the implemented methods, which have been, and continue to be, applied in discomfort glare studies, can significantly affect the results.

To prevent the use of methods affecting the results of studies, such as biased subjective assessment methods, and to encourage the comparison of the results, future studies should aim at testing the existing methods used in discomfort glare studies. The studies should either demonstrate how the method affects the results, or validate

the method if it produces reliable results. These studies can then be used as guidelines to define a unified framework for the study of discomfort glare perception. For instance, the validation of a unique glare rating scale for the study of discomfort glare perception would be highly beneficial.

Validation of Discomfort Glare Knowledge Foundations

Secondly, it would be relevant that future studies validate the foundations on which is based today's discomfort glare knowledge. In view of the findings regarding the influence of some experimental biases on the results of discomfort glare studies, highlighted in this study but also in the recent literature, the results of several studies that have formed the basis of knowledge on discomfort glare are questionable. Furthermore, two unexplained results from this study support this necessity.

On the one hand, the investigation of evalglare glare source detection parameters, detailed in a journal article [Pierson et al. 2018a] available in Appendix I, showed that applying the "smooth parameter" in evalglare produces a decrease in the background luminance, which in turn leads to a more accurate discomfort glare evaluation. Since the accuracy of discomfort glare evaluation improved by decreasing the background luminance, the weighting or even the use of this physical quantity in discomfort glare models could be reconsidered. This first unexplained result encourages therefore the reconsideration of the GC formula, described in Equation 2.1, which is the basis of contrast-based discomfort glare metrics.

On the other hand, the results in Section 6.3 seem to indicate that contrast-based metrics, namely the CGI and DGI, are slightly more efficient in evaluating the subjective assessments of discomfort glare perception of the Swiss socio-environmental group than saturation-based metrics. Inversely, saturation-based metrics, namely the E_v and L_{mean}, produce better evaluations of the subjective assessments of the Chilean and Belgian groups. These results are the opposite of what was expected: since the lighting levels were on average a bit brighter in the offices of the Swiss socio-environmental con-

text, saturation-based metrics should have been more appropriate for these situations, and inversely for the Belgian and Chilean contexts. This second unexplained result demands further research to define which type of discomfort glare occurs in which conditions, and which type of metrics should be used.

For these reasons, laboratory studies, designed in such a way that the results are not affected by experimental biases, should aim at reassessing the influence of the four main physical quantities at the basis of the contrast-based discomfort glare metrics, and at better defining in which conditions saturation-based metrics should be preferred to contrast-based metrics.

Influence of Environmental Factors and IEQ

Recent studies have started emphasizing the lack of knowledge on the combined effect of environmental factors on occupants' perception of IEQ [Torresin et al. 2018; Chinazzo 2019]. The need for a better understanding of environmental factors interactions is also supported by this study, as two environmental factors, i.e., the view through the window and the air temperature, are hypothesized to interact with discomfort glare from daylight in affecting discomfort glare perception.

Future studies should therefore aim at defining the interactions between environmental factors, so that IEQ can be improved by taking these interactions into account. In a first step, it has been recommended to investigate the combined effect of two factors at a time, given the complexity of the problem and the current state of knowledge on interactions [Chinazzo 2019].

In the field of discomfort glare, future studies should first validate the relationships of the two environmental factors with discomfort glare perception from daylight observed in this study. For this purpose, studying physiological responses in parallel with subjective assessments might be relevant, since the interactions might not only be caused by psychological processes.

Regarding the attractiveness of the view through the window, a substantial number of studies have already looked at this factor, as

seen in the state of the art. Future studies should build on that knowledge to determine which elements of the view make it attractive, and to what extent an attractive view can mitigate discomfort due to glare from daylight.

Regarding the air temperature, and more generally thermal factors, there is little evidence about their interaction with discomfort glare from daylight to date. Future studies should aim at collecting unbiased data to look at the influence that thermal factors can have on discomfort glare perception from daylight, and inversely. The study of these interactions would be especially interesting in contexts where overheating due to solar radiation is a recurrent issue.

Influence of Subject-Related Factors and Improved Evaluation

Finally, the large variation between subjects' discomfort glare perception could be in part explained by the influence of physiological and psychological factors, hence factors related to the subject. This statement is supported by the fact that the self-assessed glare sensitivity of the subject was observed to be somehow related to discomfort glare perception in this study.

Future studies should first aim to confirm the influence of factors related to the subject on discomfort glare perception from daylight, by validating a significant relationship with the self-assessed glare sensitivity for instance. In a second step, the influence of these physiological and psychological factors should be defined.

Bibliography

Abdi, H. and Williams, L. J. (2010). "Principal component analysis". In: WIREs Computational Statistics 2. DOI: 10.1002/wics.101.

Akashi, Y., Asano, S., Kakuta, Y., and Fujita, T. (2013). "Visual mechanisms of discomfort glare sensation caused by LEDs". In: CIE 2013. Paris, France.

Akashi, Y., Kojima, S., Aoki, T., and Inatani, M. (2017). "Ageing effects on discomfort glare sensation and their mechanisms". In: CIE 2017: smarter lighting for better life. Jeju, South Korea.

Aljawabra, F. and Nikolopoulou, M. (2018). "Thermal comfort in urban spaces: a cross-cultural study in the hot arid climate". In: International Journal of Biometeorology 62.10. DOI: 10.1007/s00484-018-1592-5.

Allana, A. C., Garcia-Hansen, V., Isoardi, G., and Smith, S. S. (2019). "Subjective assessments of lighting quality: a measurement review". In: LEUKOS. DOI: 10.1080/15502724.2018.1531017.

Altman, D. G. (1985). "Comparability of randomised groups". In: Journal of the Royal Statistical Society 34.1.

Altomonte, S., Kent, M. G., Tregenza, P. R., and Wilson, R. (2016a). "Visual task difficulty and temporal influences in glare response". In: Building and Environment 95. DOI: 10.1016/j.buildenv.2015.09.021.

Altomonte, Sergio, Kent, Michael G., Tregenza, Peter R., and Wilson, Robin (2016b). "Task Difficulty, Temporal Variables and Glare Response". In: PLEA 2016. Los Angeles, USA.

Ámundadóttir, M. L., St. Hilaire, M. A., Lockley, S. W., and Andersen, M. (2013). "Modelling non-visual responses to light: unifying spectral and temporal characteristics in a single model structure". In: CIE 2013. Paris, France.

Andersen, Marilyne (2004). "Innovative Bidirectional Video-Goniophotometer for Advanced Fenestration Systems". PhD dissertation. Lausanne, Switzerland: Ecole Polytechnique Fédérale de Lausanne (EPFL).

Andy Field, Graham J. Hole (20, 2002). How to Design and Report Experiments. SAGE Publications Inc. 384 pp.

Anjali, Joseph (2006). The Impact of Light on Outcomes in Healthcare Settings. Tech. rep. Concord, USA: The Center for Health Design.

Aries, M. B. C., Aarts, M. P. J., and Hoof, J. van (2015). "Daylight and health: a review of the evidence and consequences for the built environment". In: Lighting Research & Technology 47. DOI: 10.1177/1477153513509258.

Aries, M. B. C., Veitch, J. A., and Newsham, G. R. (2010). "Windows, view, and office characteristics predict physical and psychological discomfort". In: Journal of Environmental Psychology 30.4. DOI: 10.1016/j.jenvp.2009.12.004.

Arranz, I., Matesanz, B. M., Issolio, L., Menendez, J. A., Mar, S., and Aparicio, J. A. (2014). "Light adaptation in letter contrast sensitivity: the influence of optical and neural mechanisms". In: Lighting Research & Technology 46. DOI: 10.1177/1477153513484633.

ASHRAE (2013). Thermal Environmental Conditions for Human Occupancy. Atlanta, USA: American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE).

Athienitis, A. K. and Tzempelikos, A. (2002). "A methodology for simulation of daylight room illuminance distribution and light dimming for a room with a controlled shading device". In: Solar Energy 72.4. DOI: 10.1016/s0038-092x(02)00016-6.

Bach, M. (1996). "The Freiburg Visual Acuity test - Automatic measurement of visual acuity". In: Optometry & Vision Science 73.1.

Bach, M., Wesemann, W., Kolling, G., Buhren, J., Krastel, H., and Schiefer, U. (2008). "Photopic contrast sensitivity - local contrast perception". In: Ophthalmologe 105.1. DOI: 10.1007/s00347-007-1605-y.

Bargary, G., Furlan, M., Raynham, P. J., Barbur, J. L., and Smith, A. T. (2015). "Cortical hyperexcitability and sensitivity to discomfort glare". In: Neuropsychologia 69. DOI: 10.1016/j.neuropsychologia.2015.02.006.

Belcher, M. (1985). "Cultural aspects of illuminance levels". In: Lighting Design and Application 15.2.

Bellia, L., Cesarano, A., Iuliano, G.F., and Spada, G. (2008). "Daylight glare: a review of discomfort indexes". In: Visual quality and energy efficiency in indoor lighting: today for tomorrow, international workshop. Ed. by ENEA Ente per le Nuove Tecnologie L'Energia e L'Ambiente. Rome, Italy.

Bennett, C. A. (1977). "The demographic variables of discomfort glare". In: Lighting Design and Application 7.

Berman, S. M., Bullimore, M. A., Bailey, I. L., and Jacobs, R. J. (1995). "The Influence of Spectral Composition on Discomfort Glare for Large-Size Sources". In: IES 1995. New York, USA. DOI: 10.1080/00994480.1996.10748131.

Berson, D. M., Dunn, F. A., and Takao, M. (2002). "Phototransduction by retinal ganglion cells that set the circadian clock". In: Science 295.5557. DOI: 10.1126/science.1067262.

Bian, Y., Leng, T., and Ma, Y. (2018). "A proposed discomfort glare evaluation method based on the concept of 'adaptive zone'". In: Building and Environment 143. DOI: 10.1016/j.buildenv.2018.07.025.

Bian, Y. and Luo, T. (2017). "Investigation of visual comfort metrics from subjective responses in China: a study in offices with daylight". In: Building and Environment 123. DOI: 10.1016/j.buildenv.2017.07.035.

Black, J. S. and Mendenhall, M. (1991). "The U-Curve adjustment hypothesis revisited: a review and theoretical framework". In: Journal of International Business Studies 22.2.

Bluyssen, P. M., Janssen, S., Brink, L. H. van den, and Kluizenaar, Y. de (2011). "Assessment of wellbeing in an indoor office environment". In: Building and Environment 46.12. DOI: 10.1016/j.buildenv.2011.06.026.

Bommel, Wout van (2015). Road Lighting: Fundamentals, Technology and Application. Cham, Switzerland: Springer International Publishing. DOI: 10.1007/978-3-319-11466-8.

Bordass, B., Cohen, R., Standeven, M., and Leaman, A. (2001). "Assessing building performance in use 2: technical performance of the Probe buildings". In: Building Research & Information 29.2. DOI: 10.1080/09613210010008027.

Borisuit, A., Linhart, F., Scartezzini, J. L., and Münch, M. (2015). "Effects of realistic office daylighting and electric lighting conditions on visual comfort, alertness and mood". In: Lighting Research & Technology 47.2. DOI: 10.1177/1477153514531518.

Bosco, Frank A., Aguinis, Herman, Singh, Kulraj, Field, James G., and Pierce, Charles A. (2015). "Correlational effect size benchmarks". In: Journal of Applied Psychology 100.2. DOI: 10.1037/a0038047.

Boubekri, M. and Boyer, L. L. (1992). "Effect of window size and sunlight presence on glare". In: Lighting Research & Technology 24.2. DOI: 10.1177/096032719202400203.

Boubekri, Mohamed (2008). Daylighting, Architecture and Health - Building Design Strategies. Oxford, UK: Elsevier.

Bourassa, C. M. and Wirtschafter, J. D. (1966). "Mechanism of binocular increase of discomfort to high luminance". In: Nature 212.

Boyce, P. R. and Wilkins, A. (2018). "Visual discomfort indoors". In: Lighting Research & Technology 50.1. DOI: 10.1177/1477153517736467.

Boyce, Peter R. (2014). Human Factors in Lighting - Third Edition. Boca Raton, USA: Taylor & Francis Group.

Boyce, Peter, Hunter, Claudia, and Howlett, Owen (2003). The Benefits of Daylight through Windows. Tech. rep. New York, USA: Lighting Research Center - Rensselaer Polytechnic Institute.

Bühren, J., Terzi, E., Bach, M., Wesemann, W., and Kohnen, T. (2006). "Measuring contrast sensitivity under different lighting conditions: comparison

of three tests". In: Optometry & Vision Science 83.5. DOI: 1040-5488/06/8305-0290/0.

Bullough, J. D. (2009). "Spectral sensitivity for extrafoveal discomfort glare". In: Journal of Modern Optics 56.13. DOI: 10.1080/09500340903045710.

Bullough, J. D., Fu, Z., and Van Derlofske, J. (2002). "Discomfort and disability glare from halogen and HID headlamp systems". In: Society of Automotive Engineers World Congress. Ed. by Society of Automotive Engineers. Detroit, USA.

Bülow-Hübe, Helena (2008). Daylight in glazed office buildings - A comparative study of daylight availability, luminance and illuminance distribution for an office room with three different glass areas. Tech. rep. EBD-R–08/17. Lund, Sweden: Lund University.

Cabin, R. J. and Mitchell, R. J. (2000). "To Bonferroni or not to Bonferroni: when and how are the questions". In: Bulletin of the Ecological Society of America 81.3. DOI: 10.2307/20168454.

Cai, H. and Chung, T. (2012). "Evaluating discomfort glare from non-uniform electric light sources". In: Lighting Research & Technology 45.3. DOI: 10.1177/1477153512453274.

Cai, H. and Chung, T. M. (2011). "Improving the quality of high dynamic range images". In: Lighting Research & Technology 43.

Cajochen, C., Chellappa, S. L., and Schmidt, C. (2014). Circadian and Light Effects on Human Sleepiness–Alertness. Ed. by S. Garbarino, L. Nobili, and G. Costa. Milano: Springer Milan. DOI: 10.1007/978-88-470-5388-5_2.

Cammarano, S., Pellegrino, A., Lo Verso, V. R. M., and Aghemo, C. (2015). "Daylighting design for energy saving in a building global energy simulation context". In: Energy Procedia 78. DOI: 10.1016/j.egypro.2015.11.672.

Cantin, F. and Dubois, M.-C. (2011). "Daylighting metrics based on illuminance, distribution, glare and directivity". In: Lighting Research & Technology 43.3. DOI: 10.1177/1477153510393319.

Carlucci, S., Causone, F., De Rosa, F., and Pagliano, Lorenzo (2015). "A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design". In: Renewable and Sustainable Energy Reviews 47. DOI: 10.1016/j.rser.2015.03.062.

Cauwerts, Coralie (2013). "Influence of presentation modes on visual perceptions of daylit spaces". PhD dissertation. Louvain-la-Neuve, Belgium: Université catholique de Louvain (UCL).

CEN (2011a). Light and lighting - Basic terms and criteria for specifying lighting requirements. Brussels, Belgium: European Committee for Standardization.

CEN (2011b). Light and lighting - Lighting of work places. European Committee for Standardization.

Chamilothori, Kynthia (2019). "Perceptual effects of daylight patterns in architecture". PhD thesis. Ecole Polytechnique Fédérale de Lausanne (EPFL). DOI: 10.5075/epfl-thesis-9553.

Chang, C. Y. and Chen, P. K. (2005). "Human response to window views and indoor plants in the workplace". In: HortScience 40.5. DOI: 10.21273/hortsci.40.5.1354.

Chauvel, P., Collins, J. B., Dogniaux, R., and Longmore, J. (1982). "Glare from windows: current views of the problem". In: Lighting Research & Technology 14.1. DOI: 10.1177/096032718201400103.

Chen, Po-Li, Liao, Chun-Hsiang, Li, Hung-Chung, Jou, Shyh-Jye, Chen, Han-Ting, Lin, Yu-Hsin, Tang, Yu-Hsiang, Peng, Wei-Jei, Kuo, Hui-Jean, Sun, Pei-Li, and Lee, Tsung-Xian (2015). "A portable inspection system to estimate direct glare of various LED modules". In: International Conference on Optical and Photonic Engineering. Singapore, Singapore. DOI: 10.1117/12.2189599.

Chinazzo, Giorgia (2019). "Daylight and temperature in buildings: interaction effects on human responses". PhD thesis. Lausanne, Switzerland: Ecole Polytechnique Fédérale de Lausanne (EPFL). DOI: 10.5075/epfl-thesis-9342.

Chinazzo, Giorgia, Pastore, Luisa, Wienold, Jan, and Andersen, Marilyne (2018). "A field study investigation on the influence of light level on subjective thermal perception in different seasons". In: Windsor Conference: Rethinking comfort. Windsor, UK.

Christoffersen, Jens, Johnsen, Kjeld, Petersen, Erwin, Valbjorn, Ole, and Hygge, Staffan (2000). "Windows and Daylight - A Post-Occupancy Evaluation of Danish Offices". In: Lighting 2000. York, UK.

CIE (1983). Discomfort glare in the interior working environment. Tech. rep. 55:1983. Vienna, Austria: Commission Internationale de l'Eclairage.

CIE (1995). Discomfort glare in interior lighting. Tech. rep. 117:1995. Vienna, Austria: Commission Internationale de l'Eclairage.

CIE (2014). Guidance towards best practice in psychophysical procedures used when measuring relative spatial brightness. Tech. rep. 212:2014. Vienna, Austria: Commission Internationale de l'Eclairage.

Ciolino, Jody, Zhao, Wenle, Martin, Renee, and Palesch, Yuko (2011). "Quantifying the cost in power of ignoring continuous covariate imbalances in clinical trial randomization". In: Contemporary Clinical Trials 32.2. DOI: 10.1016/j.cct.2010.11.005.

Clear, R. D. (2013). "Discomfort glare: what do we actually know?" In: Lighting Research & Technology 45.2. DOI: 10.1177/1477153512444527.

Cohen, J. (1992). "A power primer". In: Psychological Bulletin 112.1.

Cohen, Jacob (1, 1988). Statistical Power Analysis for the Behavioral Sciences. Taylor & Francis Inc. 400 pp.

Cook, N. R. (2007). "Use and misuse of the Receiver Operating Characteristic curve in risk prediction". In: Circulation 115. DOI: 10.1161/CIRCULATIONAHA.106.672402.

Corrodi, M. and Spechtenhauser, K. (2, 2008). Illuminating: Natural Light in Residential Architecture. Birkhäuser Verlag GmbH. 230 pp.

D'Oca, S., Hong, T., and Langevin, J. (2018). "The human dimensions of energy use in buildings: a review". In: Renewable and Sustainable Energy Reviews 81. DOI: 10.1016/j.rser.2017.08.019.

De Boer, J.B. (1967). Public Lighting. Philips technical library. London, UK: Cleaver-Hume.

Diedenhofen, B. and Musch, J. (2015). "cocor: a comprehensive solution for the statistical comparison of correlations". In: PLoS ONE 10.4. DOI: 10.1371/journal.pone.0121945.

Do, M. T. H. and Yau, K.-W. (2010). "Intrinsically photosensitive retinal ganglion cells". In: Physiological Reviews 90.4. DOI: 10.1152/physrev.00013.2010.

Donners, M. A. H., Vissenberg, M. C. J. M., Geerdinck, L. M., Broek-Cools, J. H. F. van den, and Buddemeijer-Lock, A. (2016). "A psychophysical model of discomfort glare in both outdoor and indoor applications". In: CIE 2016: lighting quality and energy efficiency. Melbourne, Australia.

Dreyer, B. C., Coulombe, S., Whitney, S., Riemer, M., and Labbe, D. (2018). "Beyond exposure to outdoor nature: exploration of the benefits of a green building's indoor environment on wellbeing". In: Frontiers in Psychology 9. DOI: 10.3389/fpsyg.2018.01583.

Dubois, Marie-Claude (2001). Impact of Shading Devices on Daylight Quality in Offices - Simulations with Radiance. Tech. rep. TABK–01/3062. Lund, Sweden: Lund University.

Eble-Hankins, M. L. and Waters, C. E. (2005). "VCP and UGR glare evaluation systems: a look back and a way forward". In: LEUKOS 1.2. DOI: 10.1582/leukos.2004.01.02.001.

Eble-Hankins, M. L. and Waters, C. E. (2009). "Subjective impression of discomfort glare from sources of non-uniform luminance". In: LEUKOS 6.1. DOI: 10.1582/LEUKOS.2009.06.01003.

Eble-Hankins, Michelle L. (2008). "Subjective impression of discomfort glare from sources of non-uniform luminance". PhD dissertation. Lincoln, USA: University of Nebraska (UNL).

Einhorn, H. D. (1969). "A new method for the assessment of discomfort glare". In: Lighting Research & Technology 1.4. DOI: 10.1177/14771535690010040201.

Einhorn, H. D. (1979). "Discomfort glare: a formula to bridge differences". In: Lighting Research & Technology 11.2. DOI: 10.1177/147715357901100204 01.

Ellis, Paul D. (2010). The Essential Guide to Effect Sizes. New York, USA: Cambridge University Press.

Erell, Evyatar, Kaftan, Eran, and Garb, Yaakov (2014). "Daylighting for Visual Comfort and Energy Conservation in Offices in Sunny Regions". In: PLEA 2014. Ahmedabad, India.

Everitt, Brian (2011). A Whistle-Stop Tour of Statistics. New York, USA: Chapman and Hall/CRC. DOI: 10.1201/b11840.

Facchin, A., Daini, R., and Zavagno, D. (2017). "The glare effect test and the impact of age on luminosity thresholds". In: Frontiers in Psychology 8. DOI: 10.3389/fpsyg.2017.01132.

Fan, D., Painter, B., and Mardaljevic, J. (2009). "A data collection method for long-term field studies of visual comfort in real-world daylit office environments". In: PLEA 2009. Quebec City, Canada.

Faul, F., Erdfelder, E., Buchner, A., and Lang, A.-G. (2009). "Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses". In: Behavior Research Methods 41.4. DOI: 10.3758/BRM.41.4.1149.

Fechner, Gustav Theodor (1860). Elemente der psychophysik. Leipzig, Germany: Breitkopf und Härtel.

Fekete, J., Sik-Lanyi, C., and Schanda, J. (2009). "Spectral discomfort glare sensitivity investigations". In: Ophthalmic and Physiological Optics 29. DOI: 10.1111/j.1475-1313.2009.00696.x.

Ferguson, C. J. (2009). "An effect size primer: a guide for clinicians and researchers". In: Professional Psychology: Research and Practice 40.5. DOI: 10.1037/a0015808.

Field, Andy (16, 2016). An Adventure in Statistics. Ed. by Mark Kavanagh. SAGE Publications Ltd. 768 pp.

Field, Andy, Miles, Jeremy, and Field, Zoe (2012). Discovering Statistics Using R. London, UK: SAGE Publications Ltd.

Figueiro, M. G., Plitnick, B. A., Lok, A., Jones, G. E., Higgins, P., Hornick, T. R., and Rea, M. S. (2014). "Tailored lighting intervention improves measures of sleep, depression, and agitation in persons with Alzheimer's disease and related dementia living in long-term care facilities". In: Clinical Interventions in Aging 9. DOI: 10.2147/CIA.S68557.

Fisekis, K., Davies, M., Kolokotroni, M., and Langford, P. (2003). "Prediction of discomfort glare from windows". In: Lighting Research & Technology 35.4. DOI: 10.1191/1365782803li095oa.

Flannagan, M. J. (1999). Subjective and Objective Aspects of Headlamp Glare: Effects of Size and Spectral Power Distribution. Tech. rep. UMTRI-99-36. Ann Arbor, USA: University of Michigan.

Flannagan, M. J., Weintraub, D. J., and Sivak, M. (1990). Context Effects on Discomfort Glare : Task and Stimulus Factors. Tech. rep. UMTRI-90-35. Ann Arbor, USA: University of Michigan.

Flannagan, Michael J., Sivak, Michael, Gellatly, Andrew W., and Luoma, J. (1992). A Field Study of Discomfort Glare from High-Intensity Discharge Headlamps. Tech. rep. UMTRI-91-42. Ann Arbor, USA: University of Michigan.

Fotios, S. (2015). "Research note: uncertainty in subjective evaluation of discomfort glare". In: Lighting Research & Technology 47.3. DOI: 10.1177/1477153515574985.

Fotios, S. (2018). "Using category rating to evaluate the lit environment: is a meaningful opinion captured?" In: LEUKOS. DOI: 10.1080/15502724.2018.1500181.

Fotios, S. and Cheal, C. (2010). "Stimulus range bias explains the outcome of preferred-illuminance adjustments". In: Lighting Research & Technology 42. DOI: 10.1177/1477153509356018.

Fotios, Steve, Logadóttir, Ásta, Cheal, Chris, and Christoffersen, Jens (2011). "Using adjustment to define preferred illuminances: Do the results have any value?" In: CIE 2011. Sun City, South Africa.

Fox, John and Weisberg, Sanford (2019). An R Companion to Applied Regression. Third. Thousand Oaks CA: Sage.

Franzetti, C., Fraisse, G., and Achard, G. (2004). "Influence of the coupling between daylight and artificial lighting on thermal loads in office buildings". In: Energy and Buildings 36.2. DOI: 10.1016/j.enbuild.2003.10.005.

Galasiu, A. D. and Veitch, J. A. (2006). "Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review". In: Energy and Buildings 38.7. DOI: 10.1016/j.enbuild.2006.03.001.

Garland, R. (1991). "The mid-point on a rating scale: is it desirable?" In: Marketing Bulletin 2.3.

Gauthier, T. D. (2001). "Detecting trends using Spearman's rank correlation coefficient". In: Environmental Forensics 2.4. DOI: 10.1080/713848278.

Geerdinck, L. M., Van Gheluwe, J. R., and Vissenberg, M. C. J. M. (2014). "Discomfort glare perception of non-uniform light sources in an office setting". In: Journal of Environmental Psychology 39. DOI: 10.1016/j.jenvp.2014.04.002.

Geerdinck, Leonie M. (2012). "Glare perception in terms of acceptance and comfort". Master thesis. Eindhoven, The Netherlands: Eindhoven University of Technology (TUE).

Gellatly, Andrew W. and Weintraub, D. J. (1990). User reconfigurations of the De Boer rating scale for discomfort glare. Tech. rep. UMTRI-90-20. Ann Arbor, USA: University of Michigan.

Gherri, B. (2015). Assessment of Daylight Performance in Buildings: Methods and Design Strategies. WIT Press.

Goovaerts, C., Descamps, F., and Jacobs, V. A. (2017). "Shading control strategy to avoid visual discomfort by using a low-cost camera: a field study of

two cases". In: Building and Environment 125. DOI: 10.1016/j.buildenv.2017.08.030.

Green, S. B. (1991). "How many subjects does it take to do a regression analysis ?" In: Multivariate Behavioral Research 26.3. DOI: 10.1207/s15327906mbr2603_7.

Hansen, Peter, Sarey Khanie, Mandana, Kuhn, T. E., Christoffersen, Jens, Wienold, Jan, and Andersen, Marilyne (2016). "Glare Caused By Contrast Between Task And Immediate Surround: An Evaluation Of Luminance Distribution In The Field Of View". In: CIE 2016: lighting quality and energy efficiency. Melbourne, Australia.

Hattar, S., Liao, H. W., Takao, M., Berson, D. M., and Yau, K. W. (2002). "Melanopsin-containing retinal ganglion cells: architecture, projections, and intrinsic photosensitivity". In: Science 295.5557. DOI: 10.1126/science.1069609.

Hayes, Richard J. and Moulton, Lawrence H. (2017). Cluster Randomised Trials - Second Edition. Chapman & hall/crc biostatistics series. Boca Raton: CRC Press.

Hellinga, Hester IJbeltje (2013). "Daylight and View - The Influence of Windows on the Visual Quality of Indoor Spaces". PhD dissertation. Delft, The Netherlands: Technische Universiteit Delft (TUD).

Hensen, C. L. (2018). "On the history of indoor environment and it's relation to health and wellbeing". In: REHVA Journal 55.2.

Heschong, Lisa, Wright, Roger L., and Okura, Stacia (2002a). "Daylighting Impacts on Human Performance in School". In: Journal of the Illuminating Engineering Society 31.2. DOI: 10.1080/00994480.2002.10748396.

Heschong, Lisa, Wright, Roger L., and Okura, Stacia (2002b). "Daylighting Impacts on Retail Sales Performance". In: Journal of the Illuminating Engineering Society 31.2. DOI: 10.1080/00994480.2002.10748389.

Hilz, R. and Cavonius, C. R. (1974). "Functional organization of the peripheral retina: sensitivity to periodic stimuli". In: Vision Research 14.12. DOI: 10.1016/0042-6989(74)90006-6.

Hirashima, S. Q., Katzschner, A., Ferreira, D. G., Sad de Assis, E., and Katzschner, L. (2018). "Thermal comfort comparison and evaluation in different climates". In: Urban Climate 23. DOI: 10.1016/j.uclim.2016.08.007.

Hirning, M. B., Isoardi, G. L., and Cowling, I. (2014). "Discomfort glare in open plan green buildings". In: Energy and Buildings 70. DOI: 10.1016/j.enbuild.2013.11.053.

Hirning, M. B., Isoardi, G. L., and Garcia-Hansen, V. R. (2017). "Prediction of discomfort glare from windows under tropical skies". In: Building and Environment 113. DOI: 10.1016/j.buildenv.2016.08.005.

Hirning, M. B., Lim, G. H., and Reimann, G. P. (2016). "Discomfort Glare In Energy Efficient Buildings: A Case Study in the Malaysian Context". In: CIE 2016: lighting quality and energy efficiency. Melbourne, Australia.

Hirning, Michael (2014). "The Application of Luminance Mapping to Discomfort Glare: A Modified Glare Index for Green Buildings". PhD dissertation. Queensland University of Technology (QUT).

Hirning, Michael, Isoardi, Gillian, Coyne, Steve, and Cowling, Ian (2010). "Applying the Use of High Dynamic Range Imaging Pipelines to Discomfort Glare Research". In: CIE 2010: lighting quality & energy efficiency. Vienna, Austria.

Hopkinson, R. G. (1940). "Discomfort glare in lighted streets". In: Transactions of the Illuminating Engineering Society 5.1-9. DOI: 10.1177/14771535400 0500101.

Hopkinson, R. G. (1949). "Studies of Lighting and Vision in Schools". In: Transactions of the Illuminating Engineering Society 14.8. DOI: 10.1177/14771 5354901400802.

Hopkinson, R. G. (1957). "Evaluation of glare". In: Illuminating Engineering 52.

Hopkinson, R. G. (1963). Architectural Physics: Lighting. HMSO.

Hopkinson, R. G. (1971). "Glare from windows - using the glare index in daylighting design". In: Construction Research Development 3.

Hopkinson, R. G. (1972). "Glare from daylighting in buildings". In: Applied Ergonomics 3.4. DOI: 10.1016/0003-6870(72)90102-0.

Hopkinson, R. G. and Bradley, R. C. (1926). "The nature of glare". In: The Illuminating Engineer 19.12.

Hopkinson, R. G. and Bradley, R. C. (1929). "The nature and effects of glare". In: The Illuminating Engineer 22.11.

Hopkinson, R. G. and Bradley, R. C. (1960). "A study of glare from very large sources". In: Illuminating Engineering 55.

Hopkinson, R. G. and Collins, W. M. (1963). "An experimental study of the glare from a luminous ceiling". In: Transactions of the Illuminating Engineering Society 28.

Hopkinson, R. G., Petherbridge, P., and Longmore, J. (1966). Daylighting. London, UK: Butterworth-Heinemann Ltd.

Hosmer, David W., Lemeshow, Stanley, and Sturdivant, Rodney X. (2013). Applied Logistic Regression - Second Edition. Wiley Series in Probability and Statistics. Hoboken, USA: John Wiley & Sons.

Huang, W. J., Yang, Y., and Ronnier Luo, M. (2017). "Discomfort glare caused by white LEDs having different spectral power distributions". In: Lighting Research & Technology. DOI: 10.1177/1477153517704996.

Huang, Y. C. and Wang, T. (2016). "Automatic Calculation of a New China Glare Index". In: Building Simulation and Optimization 2016. Newcastle, UK.

Hubai, Zoltan (2014). qDslrDashboard. Software.

Huebner, G. M., Shipworth, D. T., Gauthier, S., Witzel, C., Raynham, P., and Chan, W. (2016). "Saving energy with light? experimental studies assessing

the impact of colour temperature on thermal comfort". In: Energy Research & Social Science 15. DOI: 10.1016/j.erss.2016.02.008.

Humphreys, M. A. (2005). "Quantifying occupant comfort: are combined indices of the indoor environment practicable?" In: Building Research & Information 33.4. DOI: 10.1080/09613210500161950.

Ichikawa, H. and Chonan, T. (1964). "Fundamental study on brightness in visual field at borderline between comfort and discomfort (BCD)". In: Journal of the Illuminating Engineering Institute of Japan 48.10. DOI: 10.2150/jieij1917.48.10_476.

IEA (2018). 2018 global status report: towards a zero-emission, efficient and resilient buildings and construction sector. Tech. rep. International Energy Agency.

IESNA (1973). "Report No. 2 from Committee on Recommendations of Quality and Quantity of Illumination: Outline of a Standard Procedure for Computing Visual Comfort Ratings for Interior Lighting". In: LEUKOS 2.3.

IESNA (1999). Recommended practice of daylighting. New York, USA: Illuminating Engineering Society of North America.

Illuminating Engineering Society of North America (IESNA) (2000). The IESNA Lighting Handbook. Ed. by Illuminating Engineering Society of North America (IESNA). 10th Edition. New York, USA: Illuminating Engineering Society (2011).

Inanici, M. (2006). "Evaluation of high dynamic range photography as a luminance data acquisition system". In: Lighting Research & Technology 38.2. DOI: 10.1191/1365782806li164oa.

Inkarojrit, Vorapat (2005). "Balancing Comfort: Occupants' Control of Window Blinds in Private Offices". PhD dissertation. Berkeley, USA: University of California (UC).

Inoue, T., Kawase, T., Ibamoto, T., Takakusa, S., and Matsuo, Y. (1988). "The development of an optimal control system for window shading devices based on investigations in office building". In: ASHRAE Transactions 104.

Inoue, Y. and Itoh, K. (1989). "Methodological study of dynamic evaluation for discomfort glare". In: Journal of Architecture, Planning and Environmental Engineering 398.

Iodice, M., Jost, S., Dumortier, D., and Gronfier, C. (2017). "An experimental protocol to objectively characterize discomfort glare using physiological measurements". In: CIE 2017: smarter lighting for better life. Jeju, South Korea.

Ishida, Kyoko, Inoue, Youko, and Uchiyama, Hironobu (2011). "Study on Lighting for the Relaxation - Influence of the Season and the Correlated Colour Temperature of Lamp". In: 27th Session of the CIE. Ed. by CIE. Sun City, South Africa.

Ishii, K., Tsukasaki, T., and Kitayama, S. (2009). "Culture and visual perception: does perceptual inference depend on culture?" In: Japanese Psychological Research 51.2. DOI: 10.1111/j.1468-5884.2009.00393.x.

ISO (2019). Ergonomics of the physical environment - Subjective judgement scales for assessing physical environments. Geneva, Switzerland: International Organization for Standardization (ISO).

Iwata, T., Kimura, K.-I., Shukuya, M., and Takano, K. (1990). "Discomfort caused by wide-source glare". In: Energy and Buildings 15.3/4. DOI: 10.1016/0378-7788(90)90013-9.

Iwata, T., Shukuya, M., Somekawa, N., and Kimura, K.-I. (1992a). "Experimental study on discomfort glare caused by windows: subjective response to glare from a simulated window". In: Journal of Architecture, Planning and Environmental Engineering 432.

Iwata, T., Taniguchi, T., and Sakuma, R. (2017a). "Automated blind control based on glare prevention with dimmable light in open-plan offices". In: Building and Environment 113. DOI: 10.1016/j.buildenv.2016.08.034.

Iwata, T. and Tokura, M. (1997). "Position Index for a glare source located below the line of vision". In: Lighting Research & Technology 29. DOI: 10.1177/14771535970290030801.

Iwata, T. and Tokura, M. (1998a). "Examination of the limitations of predicted glare sensation vote (PGSV) as a glare index for a large source: towards a comprehensive development of discomfort glare evaluation". In: Lighting Research & Technology 30.2. DOI: 10.1177/096032719803000205.

Iwata, T., Tokura, M., Shukuya, M., and Kimura, K.-I. (1992b). "Experimental study on discomfort glare caused by windows: subjective response to glare from actual windows". In: Journal of Architecture, Planning and Environmental Engineering 439.

Iwata, Toshie (2018). "Difference in Evaluation of Discomfort Glare from Windows between Middle-Eastern and Japanese Students". In: EuroSun 2018. Rapperswil, Switzerland.

Iwata, Toshie, Imai, M., Hagiwara, H., Akiyama, Y., and Sekihara, M. (2017b). "Effects of task and views on discomfort glare from windows". In: CIE 2017: smarter lighting for better life. Jeju, South Korea.

Iwata, Toshie, Nagayoshi, Kensuke, and Osterhaus, Werner K. E. (2011a). "Discomfort glare index for automated blind control". In: International Student Energy Summit 2011. Vancouver, Canada.

Iwata, Toshie and Osterhaus, W. (2010). "Assessment of Discomfort Glare in Daylit Offices using Luminance Distribution Images". In: CIE 2010: lighting quality & energy efficiency. Vienna, Austria.

Iwata, Toshie, Osterhaus, W. K. E., and Itoh, H. E (2011b). "Assessment of discomfort glare from windows with venetian blinds using luminance distribution images". In: CIE 2011. Sun City, South Africa.

Iwata, Toshie, Velds, Martine, and Van der Voorden, Marinus (1998b). "Effect of eye color on response to discomfort glare caused by a large source". In: ICHES 1998. Yokohama, Japan.

Jakubiec, J. A. (2018). "Validation of Simplified Visual Discomfort Calculations". In: Building Simulation and Optimization 2018. Cambridge, UK.

Jakubiec, J. A. and Reinhart, C. F. (2011). "The 'adaptive zone' – a concept for assessing discomfort glare throughout daylit spaces". In: Lighting Research & Technology 44. DOI: 10.1177/1477153511420097.

Jakubiec, J. A. and Reinhart, C. F. (2016). "A concept for predicting occupants' long-term visual comfort within daylit spaces". In: LEUKOS 12.4. DOI: 10.1080/15502724.2015.1090880.

Jakubiec, J. Alstan, Quek, Geraldine, and Srisamranrungruang, Thanyalak (2018). "Towards Subjectivity in Annual Climate-Based Daylight Metrics". In: Building Simulation and Optimization 2018. Cambridge, UK.

James, Gareth, Witten, Daniela, Hastie, Trevor, and Tibshirani, Robert (2013). An Introduction to Statistical Learning with Applications in R. Ed. by G. Casella, S. Fienberg, and I. Olkin. Springer Texts in Statistics. New York, USA: Springer Science+Business Media. DOI: 10.1007/978-1-4614-7138-7.

Johnson, T., Kulesa, P., Cho, Y. I., and Shavitt, S. (2005). "The relation between culture and response styles". In: Journal of Cross-Cultural Psychology 36.2. DOI: 10.1177/0022022104272905.

Kaplan, R. (2001). "The nature of the view from home". In: Environment and Behavior 33.4. DOI: 10.1177/00139160121973115.

Kar, S. S. and Ramalingam, A. (2013). "Is 30 the magic number? issues in sample size estimation". In: National Journal of Community Medicine 4.1.

Karlsen, L., Heiselberg, P., Bryn, I., and Johra, H. (2015). "Verification of simple illuminance based measures for indication of discomfort glare from windows". In: Building and Environment 92. DOI: 10.1016/j.buildenv.2015.05.040.

Karwowski, Waldemar (2006). International Encyclopedia of Ergonomics and Human Factors - Volume 1. Second edition. Vol. 1,2,3. 3. Boca Raton, USA: CRC Press.

Kenawy, Inji and Elkadi, Hisham (2013). "The impact of cultural and climatic background on thermal sensation votes". In: PLEA2013. Munich, Germany.

Kent, M. G., Cheung, T., Altomonte, S., Schiavon, S., and Lipczyńska, A. (2018a). "A Bayesian method of evaluating discomfort due to glare: the effect of order bias from a large glare source". In: Building and Environment 146. DOI: 10.1016/j.buildenv.2018.10.005.

Kent, M. G., Fotios, S., and Altomonte, S. (2018b). "An experimental study on the effect of visual tasks on discomfort due to peripheral glare". In: LEUKOS 15.1. DOI: 10.1080/15502724.2018.1489282.

Kent, M. G., Fotios, S., and Altomonte, S. (2018c). "Order effects when using Hopkinson's multiple criterion scale of discomfort due to glare". In: Building and Environment. DOI: 10.1016/j.buildenv.2018.03.022.

Kent, M. G., Fotios, S., and Cheung, T. (2019). "Stimulus range bias leads to different settings when using luminance adjustment to evaluate discomfort due to glare". In: Building and Environment 153. DOI: 10.1016/j.buildenv.2018.12.061.

Kent, M., Altomonte, S., Tregenza, P. R., and Wilson, R. (2015a). "Discomfort glare and time of day". In: Lighting Research & Technology 47. DOI: 10.1177/1477153514547291.

Kent, M., Altomonte, S., Tregenza, P., and Wilson, R. (2015b). "Temporal variables and personal factors in glare sensation". In: Lighting Research & Technology 48.6. DOI: 10.1177/1477153515578310.

Kent, M., Altomonte, S., Wilson, R., and Tregenza, P. R. (2017a). "Temporal effects on glare response from daylight". In: Building and Environment 113. DOI: 10.1016/j.buildenv.2016.09.002.

Kent, M., Fotios, S., and Altomonte, S. (2017b). "Discomfort glare evaluation: the influence of anchor bias in luminance adjustments". In: Lighting Research & Technology. DOI: 10.1177/1477153517734280.

Kent, Michael George (2016). "Temporal Effects in Glare Response". PhD dissertation. Nottingham, UK: University of Nottingham.

Kent, Michael George (2018). The importance of window view: Using an exploratory factor analysis to uncover the underlying latent dimensions. Tech. rep. Internal. Center for the Built Environment, UC Berkeley.

Kent, Michael, Altomonte, Sergio, Tregenza, Peter, and Wilson, Robin (2015c). "Time of day, temporal variables and personal factors in the subjective evaluation of glare sensation". In: PLEA 2015. Bologna, Italy.

Kent, Michael and Fotios, Steve (2017c). "Using Adjustment to Evaluate Discomfort Glare". In: Lux Europa 2017. Ljubljana, Slovenia.

Kim, D. and Mansfield, K. (2016). "A cross-cultural study on perceived lighting quality and occupants' well-being between UK and South Korea". In: Energy and Buildings 119. DOI: 10.1016/j.enbuild.2016.03.033.

Kim, J. H., Park, Y. J., Yeo, M. S., and Kim, K. W. (2009a). "An experimental study on the environmental performance of the automated blind in summer". In: Building and Environment 44.7. DOI: 10.1016/j.buildenv.2008.08.006.

Kim, J. T., Shin, J. Y., and Yun, G. Y. (2012a). "Prediction of discomfort glares from windows: influence of the subjective evaluation of window views". In: Indoor and Built Environment 21.1. DOI: 10.1177/1420326X11423157.

Kim, J., Dear, R. de, Cândido, C., Zhang, H., and Arens, E. (2013). "Gender differences in office occupant perception of indoor environmental quality (IEQ)". In: Building and Environment 70. DOI: 10.1016/j.buildenv.2013.08.022.

Kim, W., Han, H., and Kim, J. T. (2009b). "The position index of a glare source at the borderline between comfort and discomfort (BCD) in the whole visual field". In: Building and Environment 44.5. DOI: 10.1016/j.buildenv.2008.07.007.

Kim, W. and Kim, J. T. (2010). "A distribution chart of glare sensation over the whole visual field". In: Building and Environment 45.4. DOI: 10.1016/j.buildenv.2009.09.013.

Kim, W. and Kim, J. T. (2011). "A position index formula for evaluation of glare source in the visual field". In: Indoor and Built Environment 20.1. DOI: 10.1177/1420326x10389267.

Kim, W. and Kim, J. T. (2012b). "A prediction method to identify the glare source in a window with non-uniform luminance distribution". In: Energy and Buildings 46. DOI: 10.1016/j.enbuild.2011.10.037.

Kim, W. and Koga, Y. (2004). "Effect of local background luminance on discomfort glare". In: Building and Environment 39.12. DOI: 10.1016/j.buildenv.2004.05.003.

Kim, W. and Koga, Y. (2005). "Glare constant Gw for the evaluation of discomfort glare from windows". In: Solar Energy 78.1. DOI: 10.1016/j.solener.2004.05.020.

Kimura-Minoda, T. and Ayama, M. (2011). "Evaluation of discomfort glare from color LEDs and its correlation with individual variations in brightness sensitivity". In: Color research and application 36.

Kittler, Richard, Kocifaj, Miroslav, and Darula, Stanislav (2012). Daylight Science and Daylighting Technology. New York, USA: Springer Science + Business Media. DOI: 10.1007/978-1-4419-8816-4.

Klepeis, Neil E., Nelson, William C., Ott, Wayne R., Robinson, John P., Tsang, Andy M., Switzer, Paul, Behar, Joseph V., Hern, Stephen C., and Engelmann, William H. (2001). The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants. Tech. rep. Ernest Orlando Lawrence Berkeley National Laboratory.

Knez, I. and Thorsson, S. (2006). "Influences of culture and environmental attitude on thermal, emotional and perceptual evaluations of a public square". In: International Journal of Biometeorology 50.5. DOI: 10.1007/s00484-006-0024-0.

Ko, J. K. and Choi, S. Y. (2017). "Contents development for office smart lights". In: CIE 2017: smarter lighting for better life. Jeju, South Korea.

Konica Minolta, Inc. (2011). Data Management Software CL-S10w. Software.

Konis, K. (2014). "Predicting visual comfort in side-lit open-plan core zones: results of a field study pairing high dynamic range images with subjective responses". In: Energy and Buildings 77. DOI: 10.1016/j.enbuild.2014.03.035.

Konis, K. (2018). "Field evaluation of the circadian stimulus potential of daylit and non-daylit spaces in dementia care facilities". In: Building and Environment 135. DOI: 10.1016/j.buildenv.2018.03.007.

Konstantzos, I. and Tzempelikos, A. (2016). "Daylight glare evaluation with the sun in the field of view through window shades". In: Building and Environment. DOI: 10.1016/j.buildenv.2016.09.009.

Kort, Y. A. W. de (2019). "Tutorial: theoretical considerations when planning research on human factors in lighting". In: LEUKOS. DOI: 10.1080/15502724.2018.1558065.

Kort, Y. A. W. de and Veitch, J. A. (2014). "From blind spot into the spotlight". In: Journal of Environmental Psychology 39. DOI: 10.1016/j.jenvp.2014.06.005.

Kuhn, Tilman, Wienold, Jan, and Moosmann, Cornelia (2013). "Daylight glare : Age effects and their impact on glare evaluation." In: 8th Energy Forum on Solar Building Skins. Bressanone, Italy.

Kunwar, N., Cetin, K. S., Passe, U., Zhou, X., and Li, Y. (2019). "Full-scale experimental testing of integrated dynamically-operated roller shades and lighting in perimeter office spaces". In: Solar Energy 186. DOI: 10.1016/j.solener.2019.04.069.

Lamb, S. and Kwok, K. C. S. (2016). "A longitudinal investigation of work environment stressors on the performance and wellbeing of office workers". In: Applied Ergonomics 52. DOI: 10.1016/j.apergo.2015.07.010.

Laurentin, C., Bermtto, V., and Fontoynont, M. (2000). "Effect of thermal conditions and light source type on visual comfort appraisal". In: Lighting Research & Technology 32.4. DOI: 10.1177/096032710003200406.

Lavrakas, Paul (2008). Encyclopedia of Survey Research Methods. Sage Publications, Inc. DOI: 10.4135/9781412963947.

Le Roux, Brigitte and Rouanet, Henry (2010). Multiple correspondence analysis. USA: SAGE Publications.

Le, Sebastien, Josse, Julie, and Husson, Francois (2008). "FactoMineR: A Package for Multivariate Analysis". In: Journal of Statistical Software 25.1. DOI: 10.18637/jss.v025.i01.

LeBoeuf, R. A. and Shafir, E. (2006). "The long and short of it: physical anchoring effects". In: Journal of Behavioral Decision Making 19.4. DOI: 10.1002/bdm.535.

Lee, Eleanor S., Clear, Robert D., Fernandes, Luis, and Ward, Greg (2007a). Commissioning and Verification Procedures for the Automated Roller Shade System at The New York Times Headquarters, New York, New York. Tech. rep. Berkeley, USA: Lawrence Berkeley National Laboratory (LBNL).

Lee, H.-W. (2006). "Perceptive of expatriation and cross-cultural adjustment". In: The Journal of Global Business Management 2.1.

Lee, J. S. and Kim, B. S. (2007b). "Development of the nomo-graph for evaluation on discomfort glare of windows". In: Solar Energy 81.6. DOI: 10.1016/j.solener.2006.09.006.

Leite Didoné, Evelise and Ruttkay Pereira, Fernando (2011). "Integrated computer simulation for considering daylight when assessing energy efficiency in buildings". In: IBPSA 2011. Sydney, Australia.

Leocadio-Miguel, M. A., Louzada, F. M., Duarte, L. L., Areas, R. P., Alam, M., Freire, M. V., Fontenele-Araujo, J., Menna-Barreto, L., and Pedrazzoli, M. (2017). "Latitudinal cline of chronotype". In: Scientific Reports 7.1. DOI: 10.1038/s41598-017-05797-w.

Li, D. H. W. and Lam, J. C. (2000). "Measurements of solar radiation and illuminance on vertical surfaces and daylighting implications". In: Renewable Energy 20.4. DOI: 10.1016/s0960-1481(99)00126-3.

Lien, E. L. and Hammond, B. R. (2011). "Nutritional influences on visual development and function". In: Progress in Retinal and Eye Research 30.3. DOI: 10.1016/j.preteyeres.2011.01.001.

Lin, Y., Liu, Y., Sun, Y., Zhu, X., Lai, J., and Heynderickx, I. (2014). "Model predicting discomfort glare caused by LED road lights". In: Optics express 22.15. DOI: 10.1364/OE.22.018056.

Linney, Andrew Scott (2008). "Maximum Luminances and Luminance Ratios and their Impact on Users' Discomfort Glare Perception and Productivity in Daylit Offices". Master thesis. Wellington, New Zealand: Victoria University of Wellington.

Lockley, S. W. (2009). "Circadian rhythms: influence of light in humans". In: Encyclopedia of Neuroscience. Elsevier. DOI: 10.1016/b978-008045046-9.01619-3.

Logadóttir, Á., Christoffersen, J., and Fotios, S. (2011). "Investigating the use of an adjustment task to set the preferred illuminance in a workplace environment". In: Lighting Research & Technology 43.4. DOI: 10.1177/1477153511400971.

Logadóttir, Á., Fotios, S., Christoffersen, J., Hansen, S. S., Corell, D. D., and Dam-Hansen, C. (2013). "Investigating the use of an adjustment task to set preferred colour of ambient illumination". In: Color research and application 38.1. DOI: 10.1002/col.20714.

Loughman, J., Akkali, M. C., Beatty, S., Scanlon, G., Davison, P. A., O'Dwyer, V., Cantwell, T., Major, P., Stack, J., and Nolan, J. M. (2010). "The relationship between macular pigment and visual performance". In: Vision Research 50.13. DOI: 10.1016/j.visres.2010.04.009.

Luckiesh, M. and Holladay, L. L. (1925). "Glare and visibility". In: Transactions of the Illuminating Engineering Society 20.

Luckiesh, Matthew and Guth, S. K. (1949). "Brightnesses in Visual Field at Borderline Between Comfort and Discomfort (BCD)". In: National Technical Conference of the Illuminating Engineering Society. French Lick, USA.

Lulla, A. B. and Bennett, C. A. (1981). "Discomfort glare: range effects". In: LEUKOS 10.2. DOI: 10.1080/00994480.1980.10748591.

Lysgaard, S. (1955). "Adjustment in a foreign society: norwegian Fulbright grantees visiting the United States". In: International Social Science Bulletin 7.

MacGowan, David, Aspinall, Peter, Newman, Paul, Russell, Terry, and Lakowski, Ronnie (1988). Visual Quality Characteristics of the Working Environment. Tech. rep. Glasgow, UK: Inter-Institutional Research Programme.

MacGowan, David and Emery, Ashley F. (1986). "Window Architectonics in the Automated Office". In: 10th Triennial Congress of the International Council for Building Research. Washington, USA.

MacLeod, C. M. (1991). "Half a century of research on the Stroop effect: an integrative review." In: Psychological Bulletin 109.2. DOI: 10.1037/0033-2909.109.2.163.

Mahić, A., Galicinao, K., and Van Den Wymelenberg, K. (2017). "A pilot daylighting field study: testing the usefulness of laboratory-derived luminance-based metrics for building design and control". In: Building and Environment 113. DOI: 10.1016/j.buildenv.2016.11.024.

Mainster, M. A. and Turner, P. L. (2012). "Glare's causes, consequences, and clinical challenges after a century of ophthalmic study". In: American Journal of Ophthalmology 153.4. DOI: 10.1016/j.ajo.2012.01.008.

Mangkuto, R. A., Agustina, D. E., Alifah, F. A., and Suprijanto, F. (2018). "Optimisation of luminance-based metrics for lighting in an open-plan dental examination room considering psycho-physiological response of dentists". In: Optical Review. DOI: 10.1007/s10043-018-0472-x.

Mangkuto, R. A., Kurnia, K. A., Azizah, D. N., Atmodipoero, R. T., and Soelami, F. X. N. (2017). "Determination of discomfort glare criteria for daylit space in Indonesia". In: Solar Energy 149. DOI: 10.1016/j.solener.2017.04.010.

Matusiak, Barbara Szybinska (2013). "Glare from a translucent facade, evaluation with an experimental method". In: Solar Energy 97. DOI: 10.1016/j.solener.2013.08.009.

McDonald, John H. (2014). Handbook of Biological Statistics. Baltimore, USA: Sparky House.

Meerbeek, B. W., Loenen, E. J. van, Kulve, M. te, and Aarts, M. (2012). "User experience of automated blinds in offices". In: Experiencing Light 2012: Int. Conference on the Effects of Light on Wellbeing. Ed. by Experiencing Light 2012. Eindhoven, the Netherlands.

Meerbeek, Bernt, Druenen, Thijs van, Aarts, Mariëlle, Loenen, Evert van, and Aarts, Emile (2014). "Impact of Blinds Usage on Energy Consumption: Automatic Versus Manual Control". In: European Conference on Ambient Intelligence. Springer International Publishing. DOI: 10.1007/978-3-319-14112-1_14.

Midi, H., Kumar Sarkar, S., and Rana, S. (2013). "Collinearity diagnostics of binary logistic regression model". In: Journal of Interdisciplinary Mathematics 13.3. DOI: 10.1080/09720502.2010.10700699.

Miller, Scott A. (9, 2017). Developmental Research Methods. SAGE Publications, Inc. 480 pp.

Mochizuki, E. and Iwata, T. (2005). "Discomfort Glare Caused by a Window Screen with Non- uniform Luminance Distribution". In: Lux Pacifica 2005. Cairns, Australia.

Mochizuki, E., Sakamoto, S., Iwata, T., and Kimura, K.-I. (1998). "Experimental study on the effects of thermal and noise conditions on glare sensation". In: Journal of the illuminating Engineering Institute of Japan 82. DOI: 10.2150/jieij1980.82.Appendix_208.

Mochizuki, Etsuko, Iwata, Toshie, Tsukami, Shiro, and Kimura, Ken-Ichi (1997). "The comparison of glare sensation between young and old people". In: Lux Pacifica 1997. Nagoya, Japan.

Moosmann, C., Wienold, J., Wagner, A., and Wittwer, V. (2012). Ermittlung relevanter Einflussgrößen auf die subjektive Bewertung von Tageslicht zur Bewertung des visuellen Komforts in Büroräumen. Abschlussbericht. Tech. rep. Karlsruher Institut für Technologie.

Motamed, Ali, Deschamps, Laurent, and Scartezzini, Jean-louis (2015). "Validation and preliminary experiments of embedded discomfort glare assessment through a novel HDR vision sensor". In: CISBAT 2015. Lausanne, Switzerland.

Mukaka, M. M. (2012). "Statistics corner: a guide to appropriate use of correlation coefficient in medical research". In: Malawi Medical Journal; 24(3): 69-71 24.3.

Mutz, Diana and Pemantle, Robin (2011). The Perils of Randomization Checks in the Analysis of Experiments. Tech. rep. Unknown.

Narisada, Kohei and Schreuder, Duco (2004). Light Pollution Handbook. Vol. 322. Astrophysics and Space Science Library. Groningen, NL: Springer Netherlands. DOI: 10.1007/978-1-4020-2666-9.

Nazzal, A. A. (2001). "A new daylight glare evaluation method: introduction of the monitoring protocol and calculation method". In: Energy and Buildings 33.3. DOI: 10.1016/S0378-7788(00)00090-6.

Nazzal, A. A. (2005). "A new evaluation method for daylight discomfort glare". In: International Journal of Industrial Ergonomics 35.4. DOI: 10.1016/j.ergon.2004.08.010.

Newsham, G. R. (1994). "Manual control of window blinds and electric lighting: implications for comfort and energy consumption". In: Indoor Environment 3.3. DOI: 10.1177/1420326x9400300307.

Ngai, P. and Boyce, P. (2000). "The effect of overhead glare on visual discomfort". In: LEUKOS 29.2. DOI: 10.1080/00994480.2000.10748315.

Nicol, F., Wilson, M., and Chiancarella, C. (2006). "Using field measurements of desktop illuminance in European offices to investigate its dependence on outdoor conditions and its effect on occupant satisfaction, and the use of lights and blinds". In: Energy and Buildings 38.7. DOI: 10.1016/j.enbuild.2006.03.014.

Niedling, M. and Völker, S. (2017). "Influence of a glare sources spectrum on discomfort glare - a physiological explanation for a psychological phenomenon". In: CIE 2017: smarter lighting for better life. Jeju, South Korea.

Nunnally, Jum C. and Bernstein, Ira H. (1994). Psychometric theory - 3rd edition. New York, USA: McGraw-Hill.

O'Brien, W., Kapsis, K., and Athienitis, A. K. (2013). "Manually-operated window shade patterns in office buildings: a critical review". In: Building and Environment 60. DOI: 10.1016/j.buildenv.2012.10.003.

Olson, P. L. and Sivak, M. (1984). "Discomfort Glare from Automobile Headlights". In: Journal of the Illuminating Engineering Society 13.3.

Osterhaus, W. K. E. (2004). "Discomfort glare assessment and prevention for daylight applications in office environments". In: Solar Energy 79.2. DOI: 10.1016/j.solener.2004.11.011.

Osterhaus, Werner K. E. (2001). "Discomfort glare from daylight in computer offices: what do we really know?" In: Lux Europa 2001. Reykjavik, Iceland.

Osterhaus, Werner K. E. (2008). "Analysis of luminance histograms for the assessment of discomfort glare in daylit offices". In: Balkan Light 2008. Ljubljana, Slovenia.

Osterhaus, Werner K. E. (2009). "Design Guidelines for Glare-free Daylit Work Environments." In: Lux Europa 2009. Istanbul, Turkey.

Osterhaus, Werner K. E. and Bailey, Ian L. (1992). "Large Area Glare Sources and Their Effect on Discomfort and Visual Performance at Computer Workstations". In: 1992 IEEE Industry Applications Society Annual Meeting. Houston, USA.

Pagès, J. (2004). "Analyse factorielle de données mixtes". In: Revue de statistique appliquée 52.4.

Painter, B., Fan, D., and Mardaljevic, J. (2009). "Evidence-based daylight research: development of a new visual comfort monitoring method". In: Lux Europa 2009. Istanbul, Turkey.

Park, N.-K., Pae, J. Y., and Meneely, J. (2010). "Cultural preferences in hotel guestroom lighting design". In: Journal of Interior Design 36.1. DOI: 10.1111/j.1939-1668.2010.01046.x.

Paulhus, D. L. (1991). "Measures of Personality and Social Psychological Attitudes". In: ed. by J. P. Robinson, P. R. Shaver, and L. S. Wrightsman. Vol. 1 - Measures of Social Psychological Attitudes. Academic Press. Chap. 2 - Measurement and Control of Response Bias.

Paulsson, L.-E. and Sjostrand, J. (1980). "Contrast sensitivity in the presence of a glare light - theoretical concepts and preliminary clinical studies". In:

Investigative Ophthalmology & Visual Science 19.4. DOI: 0146-0404/80/040401+06$00.60/0.

Perneger, T. V. (1998). "What is wrong with Bonferroni adjustments". In: BMJ 316.7139. DOI: 10.1136/bmj.316.7139.1236.

Petherbridge, P. and Hopkinson, R. G. (1950). "Discomfort glare and the lighting of buildings". In: Lighting Research & Technology 15.2. DOI: 10.1177/147715355001500201.

Pevsner, J. (2015). Bioinformatics and Functional Genomics - Third edition. Singapore, Singapore: Wiley-Blackwell.

Phipps-Nelson, J., Redman, J. R., Dijk, D. J., and Rajaratnam, S. M. (2003). "Daytime exposure to bright light, as compared to dim light, decreases sleepiness and improves psychomotor vigilance performance". In: Sleep 26.6.

Pierson, C., Cauwerts, C., Wienold, J., and Bodart, M. (2019a). "Luminance maps for daylighting studies from High Dynamic Range photography - a tutorial". In: submitted to LEUKOS.

Pierson, C., Wienold, J., and Bodart, M. (2018a). "Daylight discomfort glare evaluation with evalglare: influence of parameters and methods on the accuracy of discomfort glare prediction". In: Buildings 8.8. DOI: 10.3390/buildings8080094.

Pierson, C., Wienold, J., and Bodart, M. (2018b). "Review of factors influencing discomfort glare perception from daylight". In: LEUKOS 14.3. DOI: 10.1080/15502724.2018.1428617.

Pierson, Clotilde, Piderit, Maria Beatriz, Wienold, Jan, and Bodart, Magali (2017). "Discomfort glare from daylighting: influence of culture on discomfort glare perception". In: CIE 2017: smarter lighting for better life. Jeju, South Korea.

Pierson, Clotilde, Sarey Khanie, Mandana, Bodart, Magali, and Wienold, Jan (2019b). "Discomfort glare cut-off values from field and laboratory studies". In: CIE 2019. Ed. by International Commission on Illumination (CIE).

Pigg, S., Reed, J., and Works, T. S. (1996). "Behavioral Aspects of Lighting and Occupancy Sensors in Private Offices : A Case Study of a University Office Building". In: ACEEE Summer Study on Energy Efficiency in Buildings.

Poulton, E. C. (1977). "Quantitative subjective assessments are almost always biased, sometimes completely misleading". In: British Journal of Psychology 68.4. DOI: 10.1111/j.2044-8295.1977.tb01607.x.

Pourhoseingholi, M. A., Baghestani, A. R., and Vahedi, M. (2012). "How to control confounding effects by statistical analysis." In: Gastroenterology and hepatology from bed to bench 5 (2).

Pulpitlova, Janka and Detkova, Patricia (1993). "Impact of the cultural and social background on the visual perception in living and working perception". In: International Symposium on Design of Amenity. Fukuoka, Japan.

R Core Team (2018). **R: A language and environment for statistical computing**. R Foundation for Statistical Computing. Vienna, Austria.

Raanaas, R. K., Patil, G. G., and Hartig, T. (2011). "Health benefits of a view of nature through the window: a quasi-experimental study of patients in a residential rehabilitation center". In: Clinical Rehabilitation 26.1. DOI: 10.1177/0269215511412800.

Ramesh, T., Prakash, R., and Shukla, K. (2010). "Life cycle energy analysis of buildings: an overview". In: Energy and Buildings 42.10. DOI: 10.1016/j.enbuild.2010.05.007.

Randler, C. (2008). "Morningness-eveningness comparison in adolescents from different countries around the world". In: Chronobiology International 25.6. DOI: 10.1080/07420520802551519.

Randler, C., Prokop, P., Sahu, S., and Haldar, P. (2014). "Cross-cultural comparison of seven morningness and sleep-wake measures from Germany, India and Slovakia". In: International Journal of Psychology 50.4. DOI: 10.1002/ijop.12098.

Ranganathan, P., Pramesh, C. S., and Aggarwal, R. (2017). "Common pitfalls in statistical analysis: logistic regression." In: Perspectives in clinical research 8 (3). DOI: 10.4103/picr.PICR_87_17.

Rea, M. S. (1982). "Calibration of subjective scaling responses". In: Lighting Research & Technology 14.3.

Reinhart, C. and Wienold, J. (2011). "The daylighting dashboard - a simulation-based design analysis for daylit spaces". In: Building and Environment 46. DOI: 10.1016/j.buildenv.2010.08.001.

Reno, Matthew J., Hansen, Clifford W., and Stein, Joshua S. (2012). Global Horizontal Irradiance Clear Sky Models: Implementation and Analysis. Tech. rep. SAND2012-2389. Sandia National Laboratories.

Revelle, William (2018). **psych: Procedures for Psychological, Psychometric, and Personality Research**. Northwestern University. Evanston, Illinois.

Rice, W. R. (1989). "Analyzing tables of statistical tests". In: Evolution 43.1. DOI: 10.2307/2409177.

Robin, Xavier, Turck, Natacha, Hainard, Alexandre, Tiberti, Natalia, Lisacek, Frederique, Sanchez, Jean-Charles, and Mueller, Markus (2011). "pROC: an open-source package for R and S+ to analyze and compare ROC curves". In: BMC Bioinformatics 12.

Rockcastle, S. F. and Andersen, M. (2013). "Celebrating contrast and daylight variability in contemporary architectural design: a typological approach". In: Lux Europa 2013. Krakow, Poland.

Rodriguez, R. G., Monteoliva, J. M., and Pattini, A. E. (2018). "A comparative field usability study of two lighting measurement protocols". In: International Journal of Human Factors and Ergonomics.

Rodriguez, R. G. and Pattini, A. (2014). "Tolerance of discomfort glare from a large area source for work on a visual display". In: Lighting Research & Technology 46.2. DOI: 10.1177/1477153512470386.

Rodriguez, R. G., Yamín Garretón, J. A., and Pattini, A. E. (2016a). "An epidemiological approach to daylight discomfort glare". In: Building and Environment. DOI: 10.1016/j.buildenv.2016.09.028.

Rodriguez, R. G., Yamín Garretón, J. A., and Pattini, A. E. (2016b). "Glare and cognitive performance in screen work in the presence of sunlight". In: Lighting Research & Technology 48.2. DOI: 10.1177/1477153515577851.

Roenneberg, T., Wirz-Justice, A., and Merrow, M. (2003). "Life between clocks: daily temporal patterns of human chronotypes". In: Journal of Biological Rhythms 18.1. DOI: 10.1177/0748730402239679.

Rosling, H., Rosling, O., and Ronnlund, A. (2018). Factfulness: ten reasons we're wrong about the world–and why things are better than you think. Flatiron Books.

Rüger, M., Gordijn, M. C. M., Beersma, D. G. M., Vries, B. de, and Daan, S. (2006). "Time-of-day-dependent effects of bright light exposure on human psychophysiology: comparison of daytime and nighttime exposure". In: American Journal of Physiology-Regulatory, Integrative and Comparative Physiology 290.5. DOI: 10.1152/ajpregu.00121.2005.

Sabry, H., Sherif, A., Gadelhak, M., and Aly, M. (2014). "Balancing the daylighting and energy performance of solar screens in residential desert buildings: examination of screen axial rotation and opening aspect ratio". In: Solar Energy 103. DOI: 10.1016/j.solener.2014.02.025.

Safari, S., Baratloo, A., Elfil, M., and Negida, A. (2016). "Evidence based emergency medicine - part 5 : Receiver Operating Curve and Area Under the Curve". In: Emergency 4.2.

Safdar, M., Ronnier Luo, M., Farhan Mughal, M., Kuai, S., Yang, Y., Fu, L., and Zhu, X. (2016). "A neural response-based model to predict discomfort glare from luminance image". In: Lighting Research & Technology. DOI: 10.1177/1477153516675910.

Sarey Khanie, M., Stoll, J., Einhäuser, W., Wienold, J., and Andersen, M. (2017). "Gaze and discomfort glare, part 1: development of a gaze-driven photometry". In: Lighting Research & Technology 49.7. DOI: 10.1177/1477153516649016.

Sarey Khanie, Mandana, Jia, Yiyuan, Wienold, Jan, and Andersen, Marilyne (2015). "A sensitivity analysis on glare detection parameters". In: IBPSA 2015. Hyderabad, India.

Saur, R. L. (1969). "Influence of physiological factors on discomfort glare level". In: Optometry & Vision Science 46.5.

Scheir, G. H., Hanselaer, P., Bracke, P., Deconinck, G., and Ryckaert, W. R. (2015). "Calculation of the Unified Glare Rating based on luminance maps for uniform and non-uniform light sources". In: Building and Environment 84.0. DOI: 10.1016/j.buildenv.2014.10.027.

Scheir, G. H., Hanselaer, P., and Ryckaert, W. R. (2017). "Pupillary light reflex, receptive field mechanism and correction for retinal position for the

assessment of visual discomfort". In: Lighting Research & Technology. DOI: 10.1177/1477153517737346.

Schloerke, Barret, Crowley, Jason, Cook, Di, Hofmann, Heike, Wickham, Hadley, Briatte, Francois, Marbach, Moritz, Thoen, Edwin, Elberg, Amos, and Larmarange, Joseph (2018). **GGally: Extension to 'ggplot2'**.

Schmidt-Clausen, H.-J. and Bindels, J. T. H. (1974). "Assessment of discomfort glare in motor vehicle lighting". In: Lighting Research & Technology 6.2. DOI: 10.1177/096032717400600204.

Segall, M. H., Campbell, D. T., and Herskovit, M. J. (1968). "The influence of culture on visual perception". In: Studies in Art Education 10.1. DOI: 10.2307/1319670.

Sekihara, Manabu, Imai, Moe, Hagiwara, Hatsumi, Akiyama, Yosihiro, Taniguchi, Tomoko, and Iwata, Toshie (2016). "Effect of Task on Discomfort Glare from Windows". In: 9th CJK Lighting Conference. Busan, Korea.

Shen, H. and Tzempelikos, A. (2012). "Daylighting and energy analysis of private offices with automated interior roller shades". In: Solar Energy 86.2. DOI: 10.1016/j.solener.2011.11.016.

Shi, W., Lockhart, T. E., and Arbab, M. (2008). "Tinted windshield and its effects on aging drivers' visual acuity and glare response". In: Safety science 46.8.

Shin, J. Y., Yun, G. Y., and Kim, J. T. (2012). "View types and luminance effects on discomfort glare assessment from windows". In: Energy and Buildings 46. DOI: 10.1016/j.enbuild.2011.10.036.

Siah, W. F., O'Brien, C., and Loughman, J. J. (2017). "Macular pigment is associated with glare-affected visual function and central visual field loss in glaucoma". In: British Journal of Ophthalmology. DOI: 10.1136/bjophthalmol-2017-310215.

Siegel, Sidney (1956). Nonparametric statistics for the behavioral sciences. Ed. by Clifford T. Morgan. McGraw-Hill Series in Psychology. New York, USA: McGraw-Hill Book Company.

Sing, T., Sander, O., Beerenwinkel, N., and Lengauer, T. (2005). "ROCR: visualizing classifier performance in R". In: Bioinformatics 21.20.

Sivak, M., Schoettle, B., Minoda, T., and Flannagan, M. J. (2005). "Short-wavelength content of LED headlamps and discomfort glare". In: LEUKOS 2.2. DOI: 10.1582/LEUKOS.2005.02.02.006.

Sivak, Michael, Flannagan, Michael J., Ensing, M., and Simmons, C. J. (1989). Discomfort glare is task dependent. Tech. rep. UMTRI-89-27. Ann Arbor, USA: University of Michigan.

Sivak, Michael, Flannagan, Michael J., Traube, Eric C., and Kojima, Shinichi (1997). The influence of stimulus duration on discomfort glare for persons with and without visual correction. Tech. rep. UMTRI-97-23. Ann Arbor, USA: University of Michigan.

Smith, P. B. (2004). "Acquiescent response bias as an aspect of cultural communication style". In: Journal of Cross-Cultural Psychology 35.1. DOI: 10.1177/0022022103260380.

Solargis (2010). Solar resource maps and GIS data for 200+ countries. website.

Stanley, Mio Jane (2016). "On The Development and Error Analysis of a High Dynamic Range Imaging System for Luminance Measurements". Master thesis. University of Colorado Boulder.

Stone, P. T. and Harker, S. D. P. (1973). "Individual and group differences in discomfort glare responses". In: Lighting Research & Technology 5.1. DOI: 10.1177/096032717300500106.

Stringham, J. M., Fuld, K., and Wenzel, A. J. (2003). "Action spectrum for photophobia". In: Journal of the Optical Society of America 20.10. DOI: 10.1364/JOSAA.20.001852.

Stringham, J. M., Fuld, K., and Wenzel, A. J. (2004). "Spatial properties of photophobia". In: Investigative Ophthalmology & Visual Science 45.10. DOI: 10.1167/iovs.04-0038.

Stringham, J. M., Garcia, P. V., Smith, P. A., McLin, L. N., and Foutch, B. K. (2011). "Macular pigment and visual performance in glare: benefits for photostress recovery, disability glare, and visual discomfort". In: Investigative Ophthalmology & Visual Science 52. DOI: 10.1167/iovs.10-6699.

Sturm, R. A. and Duffy, D. L. (2012). "Human pigmentation genes under environmental selection". In: Genome Biology 13.9. DOI: 10.1186/gb-2012-13-9-248.

Subova, A., Kittler, R., and MacGowan, D. (1991). "Results of ongoing experiments on subjective response to discomfort glare". In: Journal of the illuminating Engineering Institute of Japan 75.Appendix. DOI: 10.2150/jieij1980.75.Appendix_129.

Suk, J. Y., Schiler, M., and Kensek, K. (2013). "Development of new daylight glare analysis methodology using absolute glare factor and relative glare factor". In: Energy and Buildings 64.0. DOI: 10.1016/j.enbuild.2013.04.020.

Sutter, Yannick, Dumortier, Dominique, and Fontoynont, Marc (2006). "The use of shading systems in VDU task offices: A pilot study". In: Energy and Buildings 38.7. DOI: 10.1016/j.enbuild.2006.03.010.

Sweater-Hickcox, K., Narendran, N., Bullough, J. D., and Freyssinier, J. P. (2012). "Effect of different colored background lighting on LED discomfort glare perception". In: Twelfth International Conference on Solid State Lighting and Fourth International Conference on White LEDs and Solid State Lighting. San Diego, USA. DOI: 10.1117/12.968192.

Tashiro, T., Kawanobe, S., Kimura-Minoda, T., Kohko, S., Ishikawa, T., and Ayama, M. (2015). "Discomfort glare for white LED light sources with different spatial arrangements". In: Lighting Research & Technology 47. DOI: 10.1177/1477153514532122.

Tavakol, M. and Dennick, R. (2011). "Making sense of Cronbach's alpha". In: International Journal of Medical Education 2. DOI: 10.5116/ijme.4dfb.8dfd.

Tiller, D. K., Wang, L. M., Musser, A., and Radik, M. J. (2010). "Combined effects of noise and temperature on human comfort and performance". In: ASHRAE Transactions 116.2.

Tokura, M., Iwata, T., and Shukuya, M. (1996). "Experimental study on discomfort glare caused by windows: development of a method for evaluating discomfort glare from a large light source". In: Journal of Architecture, Planning and Environmental Engineering 489.

Torbiorn, I. (1982). Living Abroad: Personal Adjustment and Personnel Policy in the Overseas. New York, USA: John Wiley & Sons. DOI: 10.1002/tie.5060240304.

Torres, S. and Lo Verso, V. R. M. (2015). "Comparative analysis of simplified daylight glare methods and proposal of a new method based on the cylindrical illuminance". In: Energy Procedia 78. DOI: 10.1016/j.egypro.2015.11.074.

Torresin, S., Pernigotto, G., Cappelletti, F., and Gasparell, A. (2018). "Combined effects of environmental factors on human perception and objective performance: a review of experimental laboratory works". In: Indoor Air. DOI: 10.1111/ina.12457.

Tsangrassoulis, A., Kontadakis, A., and Doulos, L. (2017). "Assessing lighting energy saving potential from daylight harvesting in office buildings based on code compliance & simulation techniques: a comparison". In: Procedia Environmental Sciences 38. DOI: 10.1016/j.proenv.2017.03.127.

Tsianaka, Efthymia Eirini (2018). "A concept to evaluate dynamic daylight glare". Master thesis. Lund, Sweden: Lund University.

Tuaycharoen, N. (2011). "Windows are less glaring when there is a preferred view". In: Built-Environment Sri Lanka 9-10.1-2.

Tuaycharoen, N. and Tregenza, P. R. (2005). "Discomfort glare from interesting images". In: Lighting Research & Technology 37.4. DOI: 10.1191/1365782805li147oa.

Tuaycharoen, N. and Tregenza, P. R. (2007). "View and discomfort glare from windows". In: Lighting Research & Technology 39.2. DOI: 10.1177/1365782807077193.

Tuffery, S. (2011). Data Mining and Statistics for Decision Making Data Mining. Ed. by P. Giudici, G. H. Givens, and B. K. Mallick. Wiley Series in Computational Statistics. John Wiley & Sons.

Tyukhova, Yulia I. (2015). "Discomfort Glare From Small, High Luminance Light Sources In Outdoor Nighttime Environments". PhD dissertation. Lincoln, USA: University of Nebraska - Lincoln.

Tzempelikos, A. and Athienitis, A. K. (2007). "The impact of shading design and control on building cooling and lighting demand". In: Solar Energy 81.3. DOI: 10.1016/j.solener.2006.06.015.

UCLA: Statistical Consulting Group (2019). Data Analysis Examples. website.

Uttley, J. (2019). "Power analysis, sample size, and assessment of statistical assumptions—improving the evidential value of lighting research". In: LEUKOS. DOI: 10.1080/15502724.2018.1533851.

van den Berg, Thomas J. T. P., van Rijn, L. J., Kaper-Bongers, R., Vonhoff, D. J., Voelker-Dieben, H. J., Grabner, G., Nischler, C., Emesz, M., Wilhelm, H., Gamer, D., Schuster, A., Franssen, L., de Wit, G. C., and Coppens, J. E. (2009). "Disability Glare in the Aging Eye - Assessment and Impact on Driving". In: Journal of Optometry 2.3. DOI: 10.3921/joptom.2009.112.

Van Den Wymelenberg, K. (2012a). "Patterns of occupant interaction with window blinds: a literature review". In: Energy and Buildings 51. DOI: 10.1016/j.enbuild.2012.05.008.

Van Den Wymelenberg, K. (2014). "Visual comfort, discomfort glare, and occupant fenestration control: developing a research agenda". In: LEUKOS 10.4. DOI: 10.1080/15502724.2014.939004.

Van Den Wymelenberg, K. and Inanici, M. (2014). "A critical investigation of common lighting design metrics for predicting human visual comfort in offices with daylight". In: LEUKOS 10.3. DOI: 10.1080/15502724.2014.881720.

Van Den Wymelenberg, K. and Inanici, M. (2016). "Evaluating a new suite of luminance-based design metrics for predicting human visual comfort in offices with daylight". In: LEUKOS 12. DOI: 10.1080/15502724.2015.1062392.

Van Den Wymelenberg, K., Inanici, M., and Johnson, P. (2010). "The effect of luminance distribution patterns on occupant preference in a daylit office environment". In: LEUKOS 07.02. DOI: 10.1080/19401493.2015.1058421.

Van Den Wymelenberg, Kevin (2012b). "Evaluating Human Visual Preference and Performance in an Office Environment Using Luminance-based Metrics". PhD dissertation. Washington, USA: University of Washington (UW).

Van Derlofske, John, Bullough, John D., Dee, Peping, Chen, Jie, and Akashi, Yukio (2004). "Headlamp Parameters and Glare". In: SAE 2004 World Congress. Detroit, USA. DOI: 10.4271/2004-01-1280.

Vanhove, Jan (2014). Silly significance tests: Balance tests. Webpage.

Vásquez, N. G., Ruttkay Pereira, F. O., Pires, M. O., and Moraes, L. N. (2016). "Investigating A Method to Dynamic Assessment of Glare Using the HDR Technique". In: PLEA 2016. Los Angeles, USA.

Veitch, J. A. and Newsham, G. R. (2000). "Preferred luminous conditions in open-plan offices: research and practice recommendations". In: Lighting Research & Technology 32.4. DOI: 10.1177/096032710003200404.

Veitch, Jennifer A. (2001). "Psychological Processes Influencing Lighting Quality". In: Journal of the Illuminating Engineering Society 30.1. DOI: 10.1080/00994480.2001.10748341.

Velds, Martine (2000). "Assessment of lighting quality in office rooms with daylighting systems". PhD dissertation. Delft, The Netherlands: Technische Universiteit Delft (TUD).

Velux (2018). The effects of modern indoor living on health, wellbeing and productivity. Tech. rep. VELUX.

Vittinghoff, E. and McCulloch, C. E. (2007). "Relaxing the rule of ten events per variable in logistic and Cox regression". In: American Journal of Epidemiology 165.6. DOI: 10.1093/aje/kwk052.

Völker, S., Freyer, M., Raphael, S., and Meyborg, M. (2017). "Influence factors for discomfort glare of headlamps and a new model for its estimation". In: CIE 2017: smarter lighting for better life. Jeju, South Korea.

Vos, J. and Van Bergem-Jansen, P. M. (1995). "Greenhouse lighting side-effects: community reaction". In: Lighting Research & Technology 27.1. DOI: 10.1177/14771535950270010301.

Wang, Z., Dear, R. de, Luo, M., Lin, B., He, Y., Ghahramani, A., and Zhu, Y. (2018). "Individual difference in thermal comfort: a literature review". In: Building and Environment 138.

Ward, Greg (1987). Radiance. Software.

Ward, Greg (1993). findglare command (Radiance). Software.

Ward, Greg (2009). "The Photosphere HDR Image Browser". In: 8th International Radiance Workshop. Boston, USA.

Wasserman, L. (2003). All of Statistics - A Concise Course in Statistical Inference. Springer Texts in Statistics. Springer.

Waters, C. E., Mistrick, R. G., and Bernecker, C. A. (1995). "Discomfort glare from sources of nonuniform luminance". In: LEUKOS 24.2. DOI: 10.1080/00994480.1995.10748120.

Watkins, D. and Cheung, S. (1995). "Culture, gender, and response bias". In: Journal of Cross-Cultural Psychology 26.5. DOI: 10.1177/0022022195265003.

Watson, D., Clark, L. A., and Tellegen, A. (1988). "Development and validation of brief measures of positive and negative affect: the PANAS scales." In: Journal of Personality and Social Psychology 54 (6).

Webb, A. R. (2006). "Considerations for lighting in the built environment: non-visual effects of light". In: Energy and Buildings 38.7. DOI: 10.1016/j.enbuild.2006.03.004.

Wei, M., Houser, K. W., Orland, B., Lang, D. H., Ram, N., Sliwinski, M. J., and Bose, M. (2014). "Field study of office worker responses to fluorescent lighting of different CCT and lumen output". In: Journal of Environmental Psychology 39. DOI: 10.1016/j.jenvp.2014.04.009.

Weijters, B., Cabooter, E., and Schillewaert, N. (2010). "The effect of rating scale format on response styles: the number of response categories and response category labels". In: International Journal of Research in Marketing 27.3.

Wetzel, Eunike, Böhnke, Jan R., and Brown, Anna (2016). The ITC International Handbook of Testing and Assessment. Ed. by Frederick T.L. Long, Dave Bartram, Fanny M. Cheung, Kurt F. Geisinger, and Dragos Iliescu. Oxford University PressEditors: chap. Response biases. DOI: 10.1093/med:psych/9780199356942.003.0024.

WHO (2014). Combined or multiple exposure to health stressors in indoor built environments. Tech. rep. Bonn, Germany: World Health Organization - Regional Office for Europe.

Wienold, J. and Christoffersen, J. (2006). "Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras". In: Energy and Buildings 38.7. DOI: 10.1016/j.enbuild.2006.03.017.

Wienold, J., Iwata, T., Sarey Khanie, M., Erell, E., Kraftan, E., Rodriguez, R., Yamin Garreton, J. A., Tzempelikos, T., Konstantzos, I., Christoffersen, J., Kuhn, T. E., Pierson, C., and Andersen, M. (2019). "Cross-validation and robustness of daylight glare metrics". In: Lighting Research & Technology. DOI: 10.1177/1477153519826003.

Wienold, Jan (2007). "Dynamic simulation of blind control strategies for visual comfort and energy balance analysis". In: IBPSA 2007.

Wienold, Jan (2009a). "Daylight Glare in Offices". PhD dissertation. Freiburg, Germany: Universität Karlsruhe (TH).

Wienold, Jan (2009b). "Dynamic daylight glare evaluation". In: IBPSA 2009. Glasgow, Scotland.

Wienold, Jan and Andersen, Marilyne (2016). "Evalglare 2.0 – new features faster and more robust HDR-image evaluation". In: 15th International Radiance Workshop. Padua, Italy.

Wienold, Jan, Reetz, Christian, Kuhn, Tilmann E., and Christoffersen, Jens (2004). "Evalglare - A new RADIANCE-based tool to evaluate daylight glare in office spaces". In: 3rd International Radiance Workshop. Fribourg, Switzerland.

Wirtschafter, J. D. and Bourassa, C. M. (1966). "Binocular facilitation of discomfort with high luminances". In: Archives of Ophthalmology 75.

Wolska, A. and Sawicki, D. (2014). "Evaluation of discomfort glare in the 50+ elderly: experimental study". In: International Journal of Occupational Medicine and Environmental Health 27.3. DOI: 10.2478/s13382-014-0257-9.

Wu, Y., Kämpf, J. H., and Scartezzini, J.-L. (2019). "Automated 'eye-sight' venetian blinds based on an embedded photometric device with real-time

daylighting computing". In: Applied Energy 252. DOI: 10.1016/j.apenergy.2019.113317.

Xiong, J., Tzempelikos, A., Bilionis, I., and Karava, P. (2019). "A personalized daylighting control approach to dynamically optimize visual satisfaction and lighting energy use". In: Energy and Buildings 193. DOI: 10.1016/j.enbuild.2019.03.046.

Yamin Garretón, J. A., Colombo, E. M., and Pattini, A. E. (2018). "A global evaluation of discomfort glare metrics in real office spaces with presence of direct sunlight". In: Energy and Buildings. DOI: 10.1016/j.enbuild.2018.01.024.

Yamin Garretón, J. A., Rodriguez, R. G., Ruiz, A., and Pattini, A. E. (2014). "Degree of eye opening: a new discomfort glare indicator". In: Building and Environment 88. DOI: 10.1016/j.buildenv.2014.11.010.

Yamin Garretón, J., Rodriguez, R., and Pattini, A. (2015). "Effects of perceived indoor temperature on daylight glare perception". In: Building Research & Information 44.8. DOI: 10.1080/09613218.2016.1103116.

Yang, Y., Ronnier Luo, M., and Huang, W. J. (2016). "Assessing glare, part 3: glare sources having different colours". In: Lighting Research & Technology. DOI: 10.1177/1477153516676640.

Yang, Y., Ronnier Luo, M., and Ma, S. N. (2017). "Assessing glare, part 2: modifying Unified Glare Rating for uniform and non-uniform LED luminaires". In: Lighting Research & Technology 49. DOI: 10.1177/1477153516642622.

Zhang, Jihuang, Tu, Yan, Liu, Lu, Wang, Lili, Peng, Sheng, and Heynderickx, Ingrid (2013). "Effect of the Correlated Color Temperature of Light on Overhead Glare in Offices". In: SID Display Week. Vancouver, Canada.

Appendix A

Answers to the Open-Ended Question

ID	Socio-environmental context	Satisfaction with lighting conditions	Answers to OEQ	"What" variable	"Why" variable
1	CL	Rather unsatisfied	Creo que el tipo de luz artificial no es el más adecuado y esto se ve potenciado por la orientación norte de las ventanas, lo que genera mucho cansancio a la vista con los cambios de luz durante el día.	Artificial lighting	Type
2	CL	Rather unsatisfied	el tamaño de las ventanas es demasiado grande y al estar orientadas al norte son molestas. La iluminación artificial en ocasiones no funciona bien y su distribución quizás no es la más adecuada.	Daylighting	Discomfort glare
3	CL	Rather satisfied	prefiero mayor iluminación y no tener que controlar mediante cortinas el ingreso de esta ya que es todo muy claro o oscuro, no existen puntos medios.	General lighting	Dim lighting
4	CL	Rather satisfied	ninguna, me gusta que haya mas iluminación y poder ver lo que sucede en el exterior	0	0
5	CL	Rather satisfied	brillo que se produce en mi pantalla de la luz que proviene desde el exterir desde detras de mi silla	Computer screen	Reflections
6	CL	Rather satisfied	el reflejo de alguns muebles en mi pantalla producto de la luz que ingresa por la ventana que se encuentra detras de silla. esto no sucede en las tades	Computer screen	Reflections
7	CL	Rather satisfied	Luz fría (blanca). Prefiero luz cálida	Artificial lighting	Type
8	CL	Rather satisfied	Luz fría (artificial)	Artificial lighting	Type
9	CL	Satisfied		0	0
10	CL	Satisfied		0	0
11	CL	Satisfied		0	0
12	CL	Satisfied		0	0
13	CL	Satisfied		0	0
14	CL	Rather satisfied	al estar despejado me molesta un poco la vista al estar frente a la pantalla mucho rato	0	0
15	CL	Rather satisfied	El contraste entre zonas de luz y	Daylighting	Discomfort glare
16	CL	Rather unsatisfied	el deslumbramiento.	Daylighting	Discomfort glare
17	CL	Satisfied		0	0
18	CL	Satisfied		0	0
19	CL	Rather satisfied	No todas las luces están encendidas	Artificial lighting	Type
20	CL	Satisfied		0	0
21	CL	Satisfied		0	0
22	CL	Satisfied		0	0
23	CL	Rather satisfied	El reflejo es incomodo y debo cerrar las cortinas	Daylighting	Discomfort glare
24	CL	Rather satisfied	MUCHA LUZ ME MOLESTA	Daylighting	Discomfort glare
25	CL	Satisfied		0	0
26	CL	Rather satisfied	Exceso de luz solar	Daylighting	Discomfort glare
27	CL	Rather unsatisfied	luz artificial	Artificial lighting	NA
28	CL	Rather unsatisfied	los focos tienen mucha potencia	Artificial lighting	Discomfort glare
29	CL	Rather unsatisfied	los focos de luz artificial son muy potentes molestan la vision , sin ellos se ve muy poco	Artificial lighting	Discomfort glare
30	CL	Unsatisfied	el tipo de foco , la luminaria es muy fuerte ,	Artificial lighting	Discomfort glare
31	CL	Satisfied		0	0
32	CL	Satisfied		0	0
33	CL	Rather satisfied	Las persianas, hay una que está detrás de mi puesto de trabajo que no se encuentra buena.	0	0
34	CL	Satisfied		0	0
35	CL	Rather satisfied	no hay elementos que molesten	0	0
36	CL	Rather unsatisfied	mucha claridad	Daylighting	Discomfort glare
37	CL	Satisfied		0	0
38	CL	Satisfied		0	0
39	CL	Satisfied		0	0
40	CL	Rather unsatisfied	sol	Daylighting	Discomfort glare
41	CL	Satisfied		0	0
42	CL	Satisfied		0	0
43	CL	Unsatisfied	La intermitencia que tiene la iluminacion artificial en base a tubos fluorescentes.	Artificial lighting	Type
44	CL	Rather unsatisfied	EL REFLEJO DE LA TERMINACION DEL MOBILIARIO DE OFICINA.	Daylighting	Discomfort glare
45	CL	Rather satisfied	que la luz natural esta detras de mi	Daylighting	Type
46	CL	Satisfied		0	0
47	CL	Satisfied		0	0
48	CL	Rather unsatisfied	MUCHA LUZ DESDE MI COSTADO IZQUIERDO	Daylighting	Discomfort glare
49	CL	Unsatisfied	Fata mas florecentes de iluminación.	General lighting	Dim lighting
50	CL	Rather satisfied	La falta de florecentes o iluminaria.	General lighting	Dim lighting
51	CL	Satisfied		0	0
52	CL	Satisfied		0	0
53	CL	Rather satisfied	Calidad de las persianas, no son muy versátiles para su operación.	0	0
54	CL	Rather satisfied	Ninguna	0	0
55	CL	Satisfied		0	0
56	CL	Satisfied		0	0
57	CL	Rather satisfied	El sol por las mañanas, baja iluminación de la oficina	General lighting	Dim lighting
58	CL	Rather satisfied	LUZ POR LA VENTANA	Daylighting	Discomfort glare
59	CL	Rather satisfied	CUANDO HAY MUCHO SOL ILUMINA DEMASIADO SOBRE LA CARA Y MOLESTA PARA TRABAJAR EN EL COMPUTADOR Y NO PUEDO CAMBIAR SENTIDO DE LA PANTALLA SINO MOLESTA EL REFLEJO EN ELLA.	0	0
60	CL	Rather satisfied	ESTA AFECTADO POR LOS CAMBIOS DE LUMINOSIDAD DEL SOL, SE OSCURESE UN POCO CUANDO LAS NUBES CUBREN EL SOL	Daylighting	Type

ID	Socio-environmental context	Satisfaction with lighting conditions	Answers to OEQ	"What" variable	"Why" variable
61	CL	Satisfied		0	0
62	CL	Rather satisfied	en la tarde oscurece temprano	0	0
63	CL	Satisfied		0	0
64	CL	Rather unsatisfied	LUZ DIRECTA POR LA DERECHA	Daylighting	Discomfort glare
65	CL	Rather satisfied	luz demasiado directa en la pantalla hace que en días con sol tenga inconvenientes de ver.	Computer screen	Reflections
66	CL	Rather unsatisfied	llega por la luz de la ventana reflejo (brillo) de luz no apropiado al computador	Computer screen	Reflections
67	CL	Rather satisfied	LO QUE MAS ME MOLESTA ES EL TIPO DE LUZ, YA QUE DESPUES DE ESTAR TODA LA JORNADA LABORAL CANSA LA VISTA. CREO QUE SE DEBE A QUE LOS FLORESCENTES TIENDEN A TITILAR.	Artificial lighting	Type
68	CL	Rather satisfied	LA LUZ SE REFLEJA EN LA PANTALLA DE MI MONITOR. Y ME MOLESTA UN POCO EL REFLEJO DE LA LUZ EN LA PANTALLA.	Computer screen	Reflections
69	CL	Rather satisfied	luz natural al reflejarse en pantalla monitor	Computer screen	Reflections
70	CL	Rather satisfied	la luz natural que se refleja en el monitor	Computer screen	Reflections
71	CL	Satisfied		0	0
72	CL	Satisfied		0	0
73	CL	Rather satisfied	reflejo en la pantalla del computador	Computer screen	Reflections
74	CL	Satisfied		0	0
75	CL	Unsatisfied	La luminosidad artificial no es potente para los m2 que utilizo, como tb a esta hora (17:00 hrs) a pesar que la luz natural esta disponible, ya está oscureciendo en Punta Arenas.	General lighting	Dim lighting
76	CL	Unsatisfied	falta DE UNA MEJOR LUMINOSIDAD ARTIFICIAL	General lighting	Dim lighting
77	CL	Rather satisfied	sombra en pantalla	Computer screen	Reflections
78	CL	Rather unsatisfied	sombras en pantalla	Computer screen	Reflections
79	CL	Rather unsatisfied	la iluminacion exterior, rayos del sol que se reflejan en el monitor	Computer screen	Reflections
80	CL	Rather unsatisfied	Los rayos del sol que traviesan por la ventana y se reflejan es el monitor y escritorio en general	Daylighting	Discomfort glare
81	CL	Unsatisfied	LA LUZ QUE SE REFLEJA EN LA PANTALLA DE MI COMPUTADOR DURANTE LAS MAÑANAS Y EL REFLEJO DE LAS VENTANAS EN LA VENTANA DIVISORIA QUE ESTA SITUADO FRENTE A MI PUESTO DE TRABAJO	0	0
82	CL	Unsatisfied	LA LUZ QUE ENTRA POR LA VENTANA Y SE REFLEJA EN MI PANTALLA.	Computer screen	Reflections
83	CL	Rather satisfied	Cuando la luz solar apunta directamente sobre la pantalla del computador.	0	0
84	CL	Rather unsatisfied	Al levantar las persianas de la ventana que se encuentra tras mi puesto, ingresó mayor cantidad de luz solar que se refleja en la pantalla de mi computador, y por lo tanto ello incomoda para mantener la vista fija sobre dicha pantalla.	Computer screen	Reflections
85	CL	Satisfied		0	0
86	CL	Rather satisfied	La luz del sol es incomoda en un bajo nivel, cuando las persianas se encuentran sin bloquear la ventana. La luminosidad de los focos del recinto es ideal para realizar funciones de trabajo.	Daylighting	Discomfort glare
87	CL	Rather satisfied	no me molesta nada, todo esta bien	0	0
88	CL	Satisfied		0	0
89	CL	Satisfied		0	0
90	CL	Satisfied		0	0
91	CL	Rather satisfied	TENER POCXA LUZ NATURAL	Daylighting	Insufficiency
92	CL	Rather satisfied	LA FALTA DE LUZ NATURAL POR LAS MAÑANAS	0	0
93	CL	Rather satisfied	el reflejo de la ventana tracera de mi escritorio	Artificial lighting	Discomfort glare
94	CL	Rather satisfied	con luz apagada nada, mas sobresale la luz del computador	Computer screen	Brightness
95	CL	Satisfied		0	0
96	CL	Satisfied		0	0
97	CL	Rather satisfied	NINGUNA	0	0
98	CL	Rather satisfied	NINGUNA	0	0
99	CL	Rather satisfied	la Iluminacion directa, por la inclincacion del sol	Daylighting	Discomfort glare
100	CL	Unsatisfied	falta de luz ambiente, solo tengo luz directa	Daylighting	Discomfort glare
101	CL	Satisfied		0	0
102	CL	Satisfied		0	0
103	CL	Satisfied		0	0
104	CL	Satisfied		0	0
105	CL	Satisfied		0	0
106	CL	Rather satisfied	Bajó la luminosidad exterior.	General lighting	Dim lighting
107	CL	Unsatisfied	falta luz	General lighting	Dim lighting
108	CL	Unsatisfied	sol	Daylighting	Discomfort glare
109	CL	Satisfied		0	0
110	CL	Unsatisfied	el sol, demasiado con las persianas abiertas.	Daylighting	Discomfort glare
111	CL	Unsatisfied	El brillo del sol al tener persianas abiertas.	Daylighting	Discomfort glare
112	CL	Rather unsatisfied	La calor y el reflejo del sol que me provoca ardor a la vista con indicaciones de lagrimas.	Daylighting	Discomfort glare
113	CL	Rather satisfied	la persiana deja entrar luz de sol	Daylighting	Discomfort glare
114	CL	Rather unsatisfied	demasiada luz me molesta	Daylighting	Discomfort glare
115	CL	Satisfied		0	0
116	CL	Satisfied		0	0
117	CL	Rather satisfied	Vidrio de ventanas sucias.	Daylighting	Type
118	CL	Rather satisfied	vidrio sucio de la ventana	Daylighting	Type
119	CL	Rather satisfied	En la mañana se deben cerrar un poco las persianas por que molesta la luz	0	0
120	CL	Rather satisfied	mucha claridad	Daylighting	Discomfort glare

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121	CL	Satisfied		0	0
122	CL	Satisfied		0	0
123	CL	Satisfied		0	0
124	CL	Unsatisfied	El exceso de luminosidad sobre mi escritorio y los rayos de sol sobre mi piel.	Daylighting	Discomfort glare
125	CL	Satisfied		0	0
126	CL	Rather satisfied	Que la persiana está muy abierta y entra el sol	Daylighting	Discomfort glare
127	CL	Unsatisfied	exceso de luminosidad	Daylighting	Discomfort glare
128	CL	Unsatisfied	Exceso de luminosidad (ventanas abiertas)	Daylighting	Discomfort glare
129	CL	Satisfied		0	0
130	CL	Satisfied		0	0
131	CL	Satisfied		0	0
132	CL	Satisfied		0	0
133	CL	Satisfied		0	0
134	CL	Satisfied		0	0
135	CL	Satisfied		0	0
136	CL	Satisfied		0	0
137	CL	Satisfied		0	0
138	CL	Satisfied		0	0
139	CL	Satisfied		0	0
140	CL	Rather unsatisfied	EL CORTINAJE QUE TIENEN LAS VENTANAS LIMITAN Y DIFICULTAN LA LUMINUSIDAD, YA QUE ADEMAS LA POSICION DEL PC GENERA QUE CHOQUE LA LUZ CON LA PANTALLA DEL PC, POR LO QUE EL DESGASTE VISUAL ES MAS FUERTE A DIARIO, Y LOS DOLORES DE CABEZA MAS FRECUENTES.	General lighting	Dim lighting
141	CL	Rather satisfied	EL NO PODER BAJAR LA PERSIANA DE LA OFICINA, YA QUE CUANDO HAY SOL HACE UNA ESPECIE DE LUPA	0	0
142	CL	Rather satisfied	LA VENTANA, YA QUE ME DA LA LUZ DIRECTAMENTES	Daylighting	Discomfort glare
143	CL	Satisfied		0	0
144	CL	Rather satisfied	no tenemos cortina y llega demasiada luz solar	Daylighting	Discomfort glare
145	CL	Satisfied		0	0
146	CL	Rather satisfied	Ninguno.	0	0
147	CL	Satisfied		0	0
148	CL	Rather unsatisfied	demasiada luz se refleja en computador, molesta vision	Computer screen	Reflections
149	CL	Rather unsatisfied	El reflejo del sol que se forma en la ventana en las mañanas y a media tarde en un edificio frente a mi ventana revota luz en mi ventana.	0	0
150	CL	Rather satisfied	la luz que se refleja en el computador (pantalla)	Computer screen	Reflections
151	CL	Satisfied		0	0
152	CL	Satisfied		0	0
153	CL	Rather satisfied	el calor	0	0
154	CL	Rather unsatisfied	falta de luz	General lighting	Dim lighting
155	CL	Rather satisfied	reflejos sol en la mañana, tarde reflejo sol vidrios edificios	0	0
156	CL	Rather unsatisfied	mucha luz, no puedo enfocar bien	Daylighting	Discomfort glare
157	CL	Rather satisfied	el reflejo de los vidrios de los otros edificios	Daylighting	Discomfort glare
158	CL	Rather unsatisfied	las luces que reflejan las ventanas de los otros edificios	Daylighting	Discomfort glare
159	CL	Rather satisfied	en la tarde entra un rayo de sol por la venta, producto del reflejo del sol en la ventana del edificio que se encuentra frente del edificio donde trabajo.	0	0
160	CL	Satisfied		0	0
161	CL	Rather satisfied	no tengo molestias en la iluminación actual.	0	0
162	CL	Rather unsatisfied	LA LUZ EXTERIOR	Daylighting	Discomfort glare
163	CL	Satisfied		0	0
164	CL	Rather satisfied	Demasiada luz solar entrando por los ventanales	Daylighting	Discomfort glare
165	CL	Satisfied		0	0
166	CL	Satisfied		0	0
167	CL	Rather unsatisfied	LA LUMINOSIDAD DE LAS VENTANAS	Daylighting	Discomfort glare
168	CL	Rather unsatisfied	LAS LUCES DE LA AMPOLLETAS DEL TECHO, YA QUE LAS PERCIANAS DEBEN ESTA CERRADAS POR LA LUZ DE AFUERA	Daylighting	Discomfort glare
169	CL	Rather satisfied	que no puedo abrir la persiana, porque me ingresa mucha luminosidad que me impide enfocar correctamente el PC.	0	0
170	CL	Unsatisfied	la luminosidad detrás del PC.	Daylighting	Discomfort glare
171	BE	Satisfied		0	0
172	BE	Satisfied		0	0
173	BE	Rather satisfied	eclairage au plafond	Artificial lighting	NA
174	BE	Rather satisfied	éclairage au plafond à l'extrémité de mon poste	Artificial lighting	NA
175	BE	Rather satisfied	manque de lumière naturelle	Daylighting	Insufficiency
176	BE	Rather satisfied	peu de lumière naturelle	Daylighting	Insufficiency
177	BE	Satisfied		0	0
178	BE	Rather satisfied	Rien	0	0
179	BE	Rather satisfied	Reflets du soleil sur des parois lisses en verre tel que téléphone.	Daylighting	Discomfort glare
180	BE	Rather satisfied	Reflets surfaces lisses	Daylighting	Discomfort glare
181	BE	Satisfied		0	0
182	BE	Rather satisfied	A midi (et plus en hiver qu'en été), il y a beaucoup de lumière du soleil qui entre par la fenêtre	0	0
183	BE	Satisfied		0	0
184	BE	Unsatisfied	la luminosité	Daylighting	Discomfort glare
185	BE	Satisfied		0	0
186	BE	Rather satisfied	Trop forte luminosité due au Soleil	Daylighting	Discomfort glare

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187	BE	Satisfied		0	0
188	BE	Rather satisfied	/	0	0
189	BE	Satisfied		0	0
190	BE	Rather satisfied	Un peu trop de soleil.	Daylighting	Discomfort glare
191	BE	Rather satisfied	Rien	0	0
192	BE	Rather satisfied	Rien	0	0
193	BE	Satisfied		0	0
194	BE	Satisfied		0	0
195	BE	Rather satisfied	l'éclairage "blanc" des néons	Artificial lighting	Type
196	BE	Rather satisfied	Il manque d'une source de lumière à l'endroit où je lis.	General lighting	Dim lighting
197	BE	Rather satisfied	Mal aux yeux: néons	Artificial lighting	Type
198	BE	Rather unsatisfied	manque de lumière	General lighting	Dim lighting
199	BE	Rather satisfied	Lorsque mon écran se trouve à contre jour (vers 16h). Les stores de mon bureau sont défectueux.	0	0
200	BE	Rather satisfied	Idem	0	0
201	BE	Satisfied		0	0
202	BE	Rather satisfied	Il manque un peu de lumière et l'écran de laptop est un peu éblouissant	Computer screen	Brightness
203	BE	Satisfied		0	0
204	BE	Satisfied		0	0
205	BE	Satisfied		0	0
206	BE	Satisfied		0	0
207	BE	Satisfied		0	0
208	BE	Satisfied		0	0
209	BE	Rather satisfied	parfois la lumiere arrive direct et apres se chache (nouages improvises) donc il faut regler les rideaux tout d'un coup	0	0
210	BE	Rather unsatisfied	les lumier sont etendrees... je vu peu	General lighting	Dim lighting
211	BE	Rather satisfied	Rien	0	0
212	BE	Rather satisfied	rien	0	0
213	BE	Rather satisfied	écran	Computer screen	NA
214	BE	Rather satisfied	ecran	Computer screen	NA
215	BE	Rather satisfied	rien de spéciale. un peu très lumineux de l'extérieur	Daylighting	Discomfort glare
216	BE	Rather unsatisfied	trop de lumière de droite	Daylighting	Discomfort glare
217	BE	Satisfied		0	0
218	BE	Rather satisfied	Les rayons du soleil	Daylighting	Discomfort glare
219	BE	Satisfied		0	0
220	BE	Satisfied		0	0
221	BE	Rather unsatisfied	ébouissement	Daylighting	Discomfort glare
222	BE	Rather unsatisfied	éblouissement	Daylighting	Discomfort glare
223	BE	Rather satisfied	manque de lumière du jour	Daylighting	Insufficiency
224	BE	Unsatisfied	le soleil	Daylighting	Discomfort glare
225	BE	Rather satisfied	Un léger reflet sur l'écran de l'ordinateur	Computer screen	Reflections
226	BE	Rather satisfied	Un léger reflet sur l'écran de l'ordinateur	Computer screen	Reflections
227	BE	Rather satisfied	Soleil	Daylighting	Discomfort glare
228	BE	Rather satisfied	Soleil	Daylighting	Discomfort glare
229	BE	Satisfied		0	0
230	BE	Satisfied		0	0
231	BE	Rather satisfied	Eblouissement à certaines heures	0	0
232	BE	Rather satisfied	Un tout petit trop de soleil avec les stores ouverts	Daylighting	Discomfort glare
233	BE	Rather unsatisfied	Pas satisfait du store, ni de la lampe principale.	0	0
234	BE	Rather satisfied	Léger reflet du soleil sur le côté inférieur droit de l'écran.	Computer screen	Reflections
235	BE	Rather satisfied	plafond et sol de couleur foncée	0	0
236	BE	Rather unsatisfied	le manque de luminosité fatigue plus les yeux	General lighting	Dim lighting
237	BE	Rather satisfied	le manque de luminosité lié aux stores	General lighting	Dim lighting
238	BE	Satisfied		0	0
239	BE	Rather satisfied	If I had a bit more luminosity I could work better	General lighting	Dim lighting
240	BE	Rather satisfied	Still I would love to have more light	General lighting	Dim lighting
241	BE	Rather satisfied	extreme chaleur d'où stores fermés	General lighting	Dim lighting
242	BE	Rather satisfied	Luminosité vient de dans mon dos (fenêtre) plutôt que d'en haut.	Daylighting	Type
243	BE	Unsatisfied	Je voudrais avoir plus de fênetres ou un grand fênetre.	Daylighting	Insufficiency
244	BE	Rather unsatisfied	une fênetre grande	Daylighting	Insufficiency
245	BE	Rather satisfied	rien	0	0
246	BE	Rather satisfied	rien	0	0
247	BE	Rather satisfied	je n'apprecie pas la lumière du néon (esthetique)	Artificial lighting	Type
248	BE	Rather satisfied	rien	0	0
249	BE	Rather satisfied	L'utilisation presque systématique de lumière artificielle	Daylighting	Insufficiency
250	BE	Rather unsatisfied	Lumière de dehors, venant de la gauche	Daylighting	Discomfort glare
251	BE	Rather satisfied	le soleil derrière mon dos qui se reflète sur mon écran	Computer screen	Reflections
252	BE	Rather satisfied	le soleil dans l'écran	Computer screen	Reflections
253	BE	Satisfied		0	0
254	BE	Satisfied		0	0
255	BE	Rather satisfied	aucune	0	0
256	BE	Rather unsatisfied	manque de luminosité	General lighting	Dim lighting
257	BE	Rather satisfied	La lumière venant des fenêtres	Daylighting	Discomfort glare
258	BE	Rather satisfied	La lumière provenant de la fenêtre à ma droite.	Daylighting	Discomfort glare
259	BE	Satisfied		0	0
260	BE	Rather satisfied	Rien	0	0
261	BE	Rather satisfied	aucun	0	0
262	BE	Rather satisfied	aucun	0	0
263	BE	Rather unsatisfied	trop de lumière quand il fait beau	0	0

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264	BE	Rather satisfied	trop de lumière	Daylighting	Discomfort glare
265	BE	Rather satisfied	Lumière artificielle (néon) mal répartie sur la surface de travail.	Artificial lighting	Type
266	BE	Rather unsatisfied	L'écran de l'ordinateur est trop éblouissant par rapport à mon environnement de travail.	Computer screen	Brightness
267	BE	Rather unsatisfied	Très peu de lumière, obligation d'allumer la lumière dès le matin, jusqu'au soir	General lighting	Dim lighting
268	BE	Unsatisfied	Il fait sombre	General lighting	Dim lighting
269	BE	Rather satisfied	rien de spécial	0	0
270	BE	Rather satisfied	le soleil	Daylighting	Discomfort glare
271	BE	Satisfied		0	0
272	BE	Rather satisfied	Rien	0	0
273	BE	Satisfied		0	0
274	BE	Rather satisfied	Un peu trop de soleil	Daylighting	Discomfort glare
275	BE	Rather satisfied	Le peu de luminosité de la pièce	General lighting	Dim lighting
276	BE	Rather satisfied	La luminosité inégale	Daylighting	Discomfort glare
277	BE	Satisfied		0	0
278	BE	Rather satisfied	Moins de lumière qu'avant (la lampe est éteinte)	General lighting	Dim lighting
279	BE	Rather satisfied	Dans le courant de la matinée, le soleil a été légèrement caché par les nuages. Ce matin, il y avait un grand soleil, mon store est donc légèrement plus fermé que nécessaire par rapport à la luminosité.	General lighting	Dim lighting
280	BE	Rather unsatisfied	Le soleil est de retour et m'éblouit.	Daylighting	Discomfort glare
281	BE	Satisfied		0	0
282	BE	Satisfied		0	0
283	BE	Rather unsatisfied	Peu de fenêtre et obligation de fermer les stores à cause de la chaleur. Eclairage au néon en permanence	Daylighting	Insufficiency
284	BE	Unsatisfied	Ebloui ssment	Daylighting	Discomfort glare
285	BE	Satisfied		0	0
286	BE	Satisfied		0	0
287	BE	Rather satisfied	Aucun	0	0
288	BE	Rather satisfied	Aucun	0	0
289	BE	Rather satisfied	le soleil	Daylighting	Discomfort glare
290	BE	Rather satisfied	le soleil	Daylighting	Discomfort glare
291	BE	Satisfied		0	0
292	BE	Satisfied		0	0
293	BE	Satisfied		0	0
294	BE	Rather satisfied	en ce moment cela va va bien	0	0
295	BE	Rather unsatisfied	Les néons qui sont fort agressifs La luminosité l'après-midi quand le soleil tourne et vient sur ma droite.	Artificial lighting	Type
296	BE	Rather unsatisfied	Lumière directe venant de la fenêtre située derrière mon écran d'ordinateur.	Daylighting	Discomfort glare
297	BE	Satisfied		0	0
298	BE	Rather unsatisfied	C'est un peu sombre	General lighting	Dim lighting
299	BE	Satisfied		0	0
300	BE	Rather satisfied	Rien de spécial	0	0
301	BE	Satisfied		0	0
302	BE	Rather satisfied	le soleil	Daylighting	Discomfort glare
303	BE	Satisfied		0	0
304	BE	Rather satisfied	le soleil dans les yeux et qui réfléchit sur l'écran de l'ordinateur: obligation de fermer les stores chaque matin	0	0
305	BE	Satisfied		0	0
306	BE	Rather satisfied	Rien de bien important. Plus de lumière dans mon dos que devant moi.	Daylighting	Type
307	BE	Rather satisfied	légèrement trop lumineux	Artificial lighting	Discomfort glare
308	BE	Rather satisfied	sombre sur mon bureau mais correct pour le poste de travail	General lighting	Dim lighting
309	BE	Rather satisfied	Manque de luminosité naturelle l'après-midi	0	0
310	BE	Satisfied		0	0
311	BE	Rather satisfied	reflet du aux vitres	Daylighting	Discomfort glare
312	BE	Rather satisfied	reflet dans les vitres	Daylighting	Discomfort glare
313	BE	Rather satisfied	Les reflets sur l'écran.	Computer screen	Reflections
314	BE	Rather satisfied	L'éblouissement dû à la lumière du jour.	Daylighting	Discomfort glare
315	BE	Satisfied		0	0
316	BE	Rather satisfied	reflection of the computer screen	Computer screen	Reflections
317	BE	Rather satisfied	Les stores fermés pour cause de chaleur rendent la pièce un peu sombre	General lighting	Dim lighting
318	BE	Unsatisfied	L'intensité lumineuse sur mon écran d'ordinateur est très importante	Computer screen	Reflections
319	BE	Satisfied		0	0
320	BE	Unsatisfied	Trop de luminosité pour l'écran de l'ordinateur	Computer screen	Reflections
321	BE	Rather satisfied	trop de luminosité	Daylighting	Discomfort glare
322	BE	Rather unsatisfied	trop de luminosité	Daylighting	Discomfort glare
323	BE	Satisfied		0	0
324	BE	Satisfied		0	0
325	BE	Rather satisfied	Rien	0	0
326	BE	Unsatisfied	Trop de lumière sur l'écran d'ordinateur	Computer screen	Reflections
327	BE	Satisfied		0	0
328	BE	Rather satisfied	la chaleur	0	0
329	BE	Rather satisfied	Rien	0	0
330	BE	Satisfied		0	0

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331	BE	Rather satisfied	Rien	0	0
332	BE	Satisfied		0	0
333	BE	Satisfied		0	0
334	BE	Rather unsatisfied	Trop lumineux Lumière blanche dans le bureau	Daylighting	Discomfort glare
335	BE	Rather satisfied	Néon au-dessus du poste de travail	Artificial lighting	Type
336	BE	Rather satisfied	Plus de lumière à droite qu'à gauche	Daylighting	Discomfort glare
337	BE	Satisfied		0	0
338	BE	Rather unsatisfied	Trop forte luminosité due au soleil.	Daylighting	Discomfort glare
339	BE	Rather satisfied	Pour une durée de travail longue, la fatigue visuelle se ressent. La luminosité n'est pas toujours adaptée en ce cas.	General lighting	Dim lighting
340	BE	Rather satisfied	Pour le travail de longue durée, la luminosité de l'écran n'est pas toujours adaptée.	Computer screen	Brightness
341	BE	Rather satisfied	Eclairage indirect	Artificial lighting	NA
342	BE	Satisfied		0	0
343	JP	Satisfied		0	0
344	JP	Rather unsatisfied	画面に外の景色が映ってしまい、画面が見にくい	Computer screen	Reflections
345	JP	Satisfied		0	0
346	JP	Rather satisfied		0	0
347	JP	Rather unsatisfied	明るさの変動が大きい。	Artificial lighting	Type
348	JP	Satisfied		0	0
349	JP	Satisfied		0	0
350	JP	Satisfied		0	0
351	JP	Rather satisfied		0	0
352	JP	Rather satisfied		0	0
353	JP	Satisfied		0	0
354	JP	Rather satisfied		0	0
355	JP	Satisfied		0	0
356	JP	Satisfied		0	0
357	JP	Satisfied		0	0
358	JP	Satisfied		0	0
359	JP	Satisfied		0	0
360	JP	Rather unsatisfied	少し暗い	General lighting	Dim lighting
361	JP	Rather unsatisfied	東向きのため、朝日がまぶしい。	0	0
362	JP	Rather unsatisfied	液晶ディスプレイの背後がまぶしい	Computer screen	Brightness
363	JP	Satisfied		0	0
364	JP	Satisfied		0	0
365	JP	Satisfied		0	0
366	JP	Rather satisfied	向かいの部屋の光が強く見える	Artificial lighting	Discomfort glare
367	JP	Rather satisfied	特になし	0	0
368	JP	Rather satisfied	特になし	0	0
369	JP	Satisfied		0	0
370	JP	Rather satisfied	特に問題ありません。	0	0
371	JP	Rather satisfied	無し	0	0
372	JP	Rather satisfied	無し	0	0
373	JP	Satisfied		0	0
374	JP	Rather unsatisfied	暗い	General lighting	Dim lighting
375	JP	Rather satisfied	特にありません。	0	0
376	JP	Rather satisfied	特にありません。	0	0
377	JP	Rather unsatisfied	パソコンが反射しているところ	Computer screen	Reflections
378	JP	Rather unsatisfied	稀に、まぶしい時がある	0	0
379	JP	Rather satisfied	日中もあまり明るくない	General lighting	Dim lighting
380	JP	Rather unsatisfied	右側の窓からグレアを感じる。	Daylighting	Discomfort glare
381	JP	Rather satisfied	特になし	0	0
382	JP	Rather satisfied	特になし	0	0
383	JP	Satisfied		0	0
384	JP	Rather satisfied	暗い	General lighting	Dim lighting
385	JP	Satisfied		0	0
386	JP	Satisfied		0	0
387	JP	Satisfied		0	0
388	JP	Satisfied		0	0
389	JP	Rather satisfied	特に感じてません。 昼間の消灯時に手元のライトがあると良い。	0	0
390	JP	Rather satisfied	問題ありません。 昼の消灯時に手元の照明があると助かります。 たまに	0	0
391	JP	Rather satisfied		0	0
392	JP	Rather satisfied		0	0
393	JP	Rather satisfied	問題ありません。	0	0
394	JP	Rather satisfied	問題ありません。	0	0
395	JP	Satisfied		0	0
396	JP	Rather satisfied		0	0
397	JP	Satisfied		0	0
398	JP	Satisfied		0	0
399	JP	Satisfied		0	0
400	JP	Satisfied		0	0
401	JP	Satisfied		0	0
402	JP	Rather unsatisfied	窓からの光が少しまぶしい	Daylighting	Discomfort glare
403	JP	Satisfied		0	0
404	JP	Rather satisfied	机上面が少し暗く感じる	General lighting	Dim lighting

ID	Socio-environmental context	Satisfaction with lighting conditions	Answers to OEQ	"What" variable	"Why" variable
405	JP	Rather satisfied	特になし	0	0
406	JP	Rather satisfied	少しくらい	General lighting	Dim lighting
407	JP	Satisfied		0	0
408	JP	Rather satisfied	少々暗い	General lighting	Dim lighting
409	JP	Satisfied		0	0
410	JP	Rather unsatisfied	手元が少し暗いが、モニターを見ての作業には支障はない。目に悪いかもと思う程度。	General lighting	Dim lighting
411	JP	Satisfied		0	0
412	JP	Rather unsatisfied	周囲が暗いため、パソコンの画面が明るすぎる。	General lighting	Dim lighting
413	JP	Rather satisfied	太陽光が若干気になる	Daylighting	Discomfort glare
414	JP	Rather unsatisfied	少し暗い気がする	General lighting	Dim lighting
415	JP	Satisfied		0	0
416	JP	Rather unsatisfied	自分の周りが少し暗い	General lighting	Dim lighting
417	JP	Satisfied		0	0
418	JP	Rather satisfied	やや暗い	General lighting	Dim lighting
419	JP	Satisfied		0	0
420	JP	Satisfied		0	0
421	JP	Rather satisfied	なし	0	0
422	JP	Rather unsatisfied	まぶしいと感じる	Daylighting	Discomfort glare
423	JP	Satisfied		0	0
424	JP	Satisfied		0	0
425	JP	Satisfied		0	0
426	JP	Rather unsatisfied	やや暗い	General lighting	Dim lighting
427	JP	Satisfied		0	0
428	JP	Rather unsatisfied	光の当たり方のせいで，PCのディスプレイが見にくい	Computer screen	Reflections
429	JP	Rather satisfied	Not at all.	0	0
430	JP	Rather satisfied	Not at all	0	0
431	JP	Rather unsatisfied	パソコンに窓が映り込む	Computer screen	Reflections
432	JP	Rather unsatisfied	左側がまぶしい	Daylighting	Discomfort glare
433	JP	Satisfied		0	0
434	JP	Rather satisfied	やや暗いが、PCの画面を見る分には快適。文字の読み書きをするには暗く感じる。	General lighting	Dim lighting
435	JP	Rather satisfied	特になし	0	0
436	JP	Satisfied		0	0
437	JP	Rather unsatisfied	白い紙が見えない	Artificial lighting	Discomfort glare
438	JP	Rather unsatisfied	よく見えない	General lighting	Dim lighting
439	JP	Rather unsatisfied	夕方の西日がひどい	Daylighting	Discomfort glare
440	JP	Rather unsatisfied	窓眩しい	Daylighting	Discomfort glare
441	JP	Rather satisfied	午前中がまぶしい時がある	0	0
442	JP	Unsatisfied	暗い	General lighting	Dim lighting
443	JP	Rather unsatisfied	ブラインドが閉まらない	0	0
444	JP	Rather unsatisfied	窓面がまぶしく室奥が暗いため パソコン画面が見えにくい	Daylighting	Discomfort glare
445	JP	Rather satisfied	特にはありません	0	0
446	JP	Rather satisfied	ブラインド制御がないと少し眩しさを感じる	Daylighting	Discomfort glare
447	JP	Rather satisfied	ブラインドが空いている方の窓が眩しいことがある。	Daylighting	Discomfort glare
448	JP	Satisfied		0	0
449	JP	Rather satisfied	紙面作業では問題ないが、パソコンの作業の場合は照明の光がパソコンの画面に反射すること。 窓に関しては外に木が生えており、直接目に光が入らないので気にならない。	Computer screen	Reflections
450	JP	Rather unsatisfied	パソコンの画面が暗く見える程度	General lighting	Dim lighting
451	JP	Rather satisfied	なし	0	0
452	JP	Rather satisfied	なし	0	0
453	JP	Rather satisfied	特に問題を感じません。	0	0
454	JP	Rather unsatisfied	少し暗いです。	General lighting	Dim lighting
455	JP	Rather satisfied	照明の調節が出来るとよい。 例えば、PPTを使用時に全体が暗くなるとPC画面が明るすぎて、目が疲れる。	0	0
456	JP	Rather satisfied	特になし	0	0
457	JP	Rather satisfied	問題はない	0	0
458	JP	Rather satisfied	問題はない	0	0
459	JP	Rather satisfied	自然光があるにもかかわらず照明をつけているため目が疲れやすいと感じている	Daylighting	Insufficiency
460	JP	Rather satisfied	ブラインドが全開で外からの自然光のみの明るさの中にいるので明るさが丁度良い	0	0
461	JP	Rather satisfied	少し暗いと思う、眠い感じがある、	General lighting	Dim lighting
462	JP	Satisfied		0	0
463	JP	Satisfied		0	0
464	JP	Rather satisfied	特になし	0	0
465	JP	Rather satisfied	蛍光灯の明るさが均一でない。	Artificial lighting	Type
466	JP	Rather satisfied		0	0
467	JP	Rather satisfied	蛍光灯の色が違う箇所があるのが気になる。部分的に明るい・暗いのバラつきがある。	Artificial lighting	Type
468	JP	Rather satisfied	さきほどと比べると、ブラインドがひらいているので全体的に明るくなりよくなった。畳っているので、直接的なグレアは感じない。	0	0
469	JP	Rather satisfied	タスクライトがないとたまに暗い	0	0
470	JP	Rather satisfied	やや暗い。タスクライトが欲しい	General lighting	Dim lighting
471	JP	Rather unsatisfied	少し暗く感じる	General lighting	Dim lighting

ID	Socio-environmental context	Satisfaction with lighting conditions	Answers to OEQ	"What" variable	"Why" variable
472	JP	Rather satisfied	特になし	0	0
473	JP	Rather unsatisfied	間引き照明をしているので、常時暗い。あとビルからの反射光がすごくまぶしい。	0	0
474	JP	Rather satisfied	曇天のため特になし	0	0
475	JP	Rather satisfied	特になし。	0	0
476	JP	Satisfied		0	0
477	JP	Satisfied		0	0
478	JP	Rather satisfied	Just by the window, it may be too high	Daylighting	Discomfort glare
479	JP	Rather satisfied	少し暗い	General lighting	Dim lighting
480	JP	Rather satisfied	特になし	0	0
481	JP	Rather satisfied	なし	0	0
482	JP	Rather satisfied	なし	0	0
483	JP	Rather satisfied	全体的に少し暗い印象がある。	General lighting	Dim lighting
484	JP	Rather satisfied	特に問題は感じない。	0	0
485	JP	Rather unsatisfied	窓が塞がれて、少しくらい印象がある。	0	0
486	JP	Rather satisfied	特にありません。	0	0
487	JP	Rather satisfied	天候によって暗い時がある。	0	0
488	JP	Rather satisfied	特になし	0	0
489	JP	Satisfied		0	0
490	JP	Satisfied		0	0
491	JP	Rather satisfied	ありません	0	0
492	JP	Rather satisfied	少し明るすぎる	Daylighting	Discomfort glare
493	JP	Satisfied		0	0
494	JP	Satisfied		0	0
495	JP	Rather unsatisfied	明るすぎるときや、暗すぎるときがある。	0	0
496	JP	Rather unsatisfied	まぶしい	Daylighting	Discomfort glare
497	JP	Rather satisfied	nothing	0	0
498	JP	Rather satisfied	窓の方を向くと少し眩しい	Daylighting	Discomfort glare
499	JP	Rather satisfied	特になし	0	0
500	JP	Rather satisfied	特になし	0	0
501	JP	Satisfied		0	0
502	JP	Rather unsatisfied	暗い	General lighting	Dim lighting
503	JP	Rather satisfied	明るさが安定しない。	Daylighting	Discomfort glare
504	JP	Rather unsatisfied	右方にある窓からの光がまぶしい	Daylighting	Discomfort glare
505	JP	Rather satisfied	時間帯によって明るさの差が大きいと感じることがある。	Daylighting	Discomfort glare
506	JP	Rather unsatisfied	外の光がまぶしく感じる。	Daylighting	Discomfort glare
507	JP	Rather satisfied	特に問題なし	0	0
508	JP	Rather satisfied	特に問題なし	0	0
509	JP	Rather satisfied	None.	0	0
510	JP	Rather satisfied	None.	0	0
511	JP	Rather satisfied	昼光がデスク作業をしているときにまぶしいときがある。	0	0
512	JP	Rather satisfied	昼光がまぶしい。	Daylighting	Discomfort glare
513	JP	Rather satisfied	特にありません。	0	0
514	JP	Rather satisfied	特にありません。	0	0
515	JP	Rather satisfied	ありません	0	0
516	JP	Rather satisfied	なし	0	0
517	JP	Rather satisfied	まぶしいときにブラインドを閉めなければならない点が問題です。	0	0
518	JP	Rather satisfied	時間によってはブラインドを閉めなければならない点が問題です。	Daylighting	Discomfort glare
519	JP	Rather satisfied	ブラインドをフルオープンにしたときは、北側とはいえまぶしいかな？	0	0
520	JP	Rather unsatisfied	ブラインドをあけるとまぶしい	Daylighting	Discomfort glare
521	JP	Rather unsatisfied	デスクトップPCのモニターが眩しいときがある。 特に午前中。	Computer screen	Reflections
522	JP	Rather unsatisfied	少し暗い　書類が見づらい	Computer screen	Reflections
523	JP	Satisfied		0	0
524	JP	Rather satisfied	特になし	0	0
525	JP	Rather satisfied	特になし	0	0
526	JP	Rather satisfied	特になし	0	0
527	JP	Rather satisfied	特に問題はない	0	0
528	JP	Rather satisfied	特になし	0	0
529	JP	Satisfied		0	0
530	JP	Rather satisfied	no	0	0
531	JP	Rather satisfied	特になし	0	0
532	JP	Rather satisfied	やや左目側の窓が明るい	Daylighting	Discomfort glare
533	JP	Satisfied		0	0
534	JP	Rather satisfied	太陽の角度により、眩しい時がある	Daylighting	Discomfort glare
535	JP	Satisfied		0	0
536	JP	Satisfied		0	0
537	JP	Satisfied		0	0
538	JP	Rather satisfied	特になし	0	0
539	JP	Rather satisfied	なし	0	0
540	JP	Rather satisfied	なし	0	0
541	JP	Satisfied		0	0
542	JP	Satisfied		0	0
543	JP	Rather satisfied	No problem	0	0
544	JP	Rather satisfied	No problem	0	0

ID	Socio-environmental context	Satisfaction with lighting conditions	Answers to OEQ	"What" variable	"Why" variable
545	JP	Rather satisfied		0	0
546	JP	Rather satisfied		0	0
547	JP	Satisfied		0	0
548	JP	Rather satisfied	一部ブラインドが壊れており、直射日光が入ってくるとまぶしい。	Daylighting	Discomfort glare
549	JP	Satisfied		0	0
550	JP	Satisfied		0	0
551	JP	Rather unsatisfied	少しくらい	0	0
552	JP	Rather unsatisfied	少しくらい	0	0
553	JP	Rather unsatisfied	特に午後窓からの光がまぶしい時がある	Daylighting	Discomfort glare
554	JP	Rather unsatisfied	特に午後窓からの光がまぶしい時がある	Daylighting	Discomfort glare
555	JP	Satisfied		0	0
556	JP	Rather satisfied	窓側の光が少し気になる。	Daylighting	Discomfort glare
557	JP	Rather satisfied	外光が眩しい時がある。	Daylighting	Discomfort glare
558	JP	Rather unsatisfied	特になし	0	0
559	JP	Unsatisfied	1）外光がまぶしくDisplayが、見ずらい。 DisplayのBacklightは、眩しくないように、低くしている。 2）Ceiling lamp(FL)にShadingが付いていないので眩しい。	Daylighting	Discomfort glare
560	JP	Unsatisfied	1）窓からの外光がDisplayにあたり、見えずらい。 2）Ceiling lampにShadingがないため、FLの光が目に入る	Daylighting	Discomfort glare
561	JP	Rather unsatisfied	夕方、西日で眩しい事がある	0	0
562	JP	Rather unsatisfied	西日がまぶしい、調光がない	Daylighting	Discomfort glare
563	JP	Satisfied		0	0
564	JP	Rather unsatisfied	視界がちかちかする	0	0
565	JP	Rather satisfied	特に問題ないです。	0	0
566	JP	Unsatisfied	外壁からの反射光がまぶしい	Daylighting	Discomfort glare
567	JP	Rather satisfied	なし	0	0
568	JP	Rather unsatisfied	まぶしい	Daylighting	Discomfort glare
569	JP	Rather satisfied	特になし	0	0
570	JP	Unsatisfied	まぶしい	Daylighting	Discomfort glare
571	JP	Satisfied		0	0
572	JP	Rather unsatisfied	窓の外の壁がまぶしい	Daylighting	Discomfort glare
573	JP	Rather satisfied	たまに直射光や拡散光がまぶしい時がある。	0	0
574	JP	Rather unsatisfied	明らかに窓側がまぶしい	Daylighting	Discomfort glare
575	JP	Rather satisfied	なし	0	0
576	JP	Rather unsatisfied	少しまぶしい	Daylighting	Discomfort glare
577	JP	Rather satisfied	すこし明るすぎる	Daylighting	Discomfort glare
578	JP	Rather unsatisfied	まぶしさを感じる、明るすぎる	Daylighting	Discomfort glare
579	JP	Rather satisfied	窓面からの光がやや眩しい	Daylighting	Discomfort glare
580	JP	Unsatisfied	窓からの光がまぶしすぎて、長時間の集中作業が困難。	Daylighting	Discomfort glare
581	CH	Satisfied		0	0
582	CH	Satisfied		0	0
583	CH	Rather satisfied	Reflets	Computer screen	Reflections
584	CH	Rather satisfied	Un peu sombre	General lighting	Dim lighting
585	CH	Satisfied		0	0
586	CH	Satisfied		0	0
587	CH	Satisfied		0	0
588	CH	Rather satisfied	none	0	0
589	CH	Satisfied		0	0
590	CH	Satisfied		0	0
591	CH	Rather satisfied	none	0	0
592	CH	Rather satisfied	none	0	0
593	CH	Satisfied		0	0
594	CH	Satisfied		0	0
595	CH	Rather satisfied	le vis-à-vis (rez de chaussée)	0	0
596	CH	Rather satisfied	la vue depuis mon bureau	0	0
597	CH	Satisfied		0	0
598	CH	Rather satisfied	Reflection in the monitor	Computer screen	Reflections
599	CH	Satisfied		0	0
600	CH	Rather unsatisfied	Too much bright light from the window.	Daylighting	Discomfort glare
601	CH	Rather satisfied	Selon l'heure, le soleil se réfléchi sur les écran (il se trouve derrière l'écran), rendant le contraste sur ceux-ci difficile a voir.	0	0
602	CH	Rather unsatisfied	Trop de lumière sur le côté gauche (fenêtre), m'éblouit dés que je tourne la tête dans cette direction.	Daylighting	Discomfort glare
603	CH	Satisfied		0	0
604	CH	Rather satisfied	Whiteboards and desk not well lit	General lighting	Dim lighting
605	CH	Satisfied		0	0
606	CH	Rather unsatisfied	brightness and warmth	Daylighting	Discomfort glare
607	CH	Rather satisfied	Intense light during mornings	0	0
608	CH	Rather unsatisfied	Still the intense light on one part of my office	Daylighting	Discomfort glare
609	CH	Satisfied		0	0
610	CH	Unsatisfied	Le soleil à moitié dans les yeux et sur l'écran rend les conditions de travail très compliquées, surtout très désagréables...	Daylighting	Discomfort glare
611	CH	Rather satisfied	Reflection from the bottom of the grating on the window which is impossible to remove with black blinds. Would be better to have non-reflective surface outside of the window that is holding the grating. Black blinds do not completely keep out sunlight, which is not nice when the sun is directly in the window and in your face.	Daylighting	Discomfort glare
612	CH	Unsatisfied	so much light that it is impossible to work. Having to squint my eyes in order to keep them open.	Daylighting	Discomfort glare

ID	Socio-environmental context	Satisfaction with lighting conditions	Answers to OEQ	"What" variable	"Why" variable
613	CH	Rather unsatisfied	light penetrating a gridded window blinds in a rather dark room makes me feel like in a basement room with little windows.	Daylighting	Type
614	CH	Rather satisfied	Not much. Maybe the contrast of light at the opposite wall.	Daylighting	Discomfort glare
615	CH	Rather satisfied	Right now nothing	0	0
616	CH	Rather unsatisfied	Sun is shining directly into my eyes :(	Daylighting	Discomfort glare
617	CH	Satisfied		0	0
618	CH	Rather satisfied	Glare	Daylighting	Discomfort glare
619	CH	Rather satisfied	window	Daylighting	Discomfort glare
620	CH	Rather satisfied	Glare	Daylighting	Discomfort glare
621	CH	Rather satisfied	too much light from the window	Daylighting	Discomfort glare
622	CH	Rather unsatisfied	too much light from the window too much light reflected from the table	Daylighting	Discomfort glare
623	CH	Satisfied		0	0
624	CH	Satisfied		0	0
625	CH	Satisfied		0	0
626	CH	Rather satisfied	Sharp contrast between some areas of my desk that are brightly lit, with most of it being dimly lit instead.	Daylighting	Discomfort glare
627	CH	Rather satisfied	could be more natural light	Daylighting	Insufficiency
628	CH	Satisfied		0	0
629	CH	Rather unsatisfied	The low sun in the late afternoon.	0	0
630	CH	Rather unsatisfied	Glare from the high sun	Daylighting	Discomfort glare
631	CH	Satisfied		0	0
632	CH	Rather satisfied	Trop de soleil/lumière	Daylighting	Discomfort glare
633	CH	Satisfied		0	0
634	CH	Rather satisfied	the walls block my view	0	0
635	CH	Satisfied		0	0
636	CH	Satisfied		0	0
637	CH	Satisfied		0	0
638	CH	Satisfied		0	0
639	CH	Satisfied		0	0
640	CH	Satisfied		0	0
641	CH	Satisfied		0	0
642	CH	Rather satisfied	bright reflection in front of the window	Daylighting	Discomfort glare
643	CH	Satisfied		0	0
644	CH	Rather unsatisfied	La lumiere du soleil reflecté sur mon bureau eblouisse ma vision de mon ecran secondaire.	Daylighting	Discomfort glare
645	CH	Satisfied		0	0
646	CH	Satisfied		0	0
647	CH	Satisfied		0	0
648	CH	Rather satisfied	Too much light for the screen. Otherwise would be perfect	Computer screen	Reflections
649	CH	Satisfied		0	0
650	CH	Satisfied		0	0
651	CH	Satisfied		0	0
652	CH	Satisfied		0	0
653	CH	Satisfied		0	0
654	CH	Rather satisfied	Too much lighting for now (curtain is open)	Daylighting	Discomfort glare
655	CH	Unsatisfied	sun directly comes to my eyes	Daylighting	Discomfort glare
656	CH	Unsatisfied	Sun	Daylighting	Discomfort glare
657	CH	Rather satisfied	The fluorescent light can be too bright sometimes during the day time	0	0
658	CH	Rather satisfied	The lighting of my computer screen and the undesired reflections on my screen	Computer screen	Reflections
659	CH	Satisfied		0	0
660	CH	Rather satisfied	an opaque window	0	0
661	CH	Satisfied		0	0
662	CH	Rather satisfied	La reflection du soleil contre le sol claire m'ébloui un peu	Daylighting	Discomfort glare
663	CH	Satisfied		0	0
664	CH	Rather satisfied	none	0	0
665	CH	Rather satisfied	None	0	0
666	CH	Rather satisfied	None	0	0
667	CH	Rather unsatisfied	not enough daylight	Daylighting	Insufficiency
668	CH	Rather unsatisfied	too dark	General lighting	Dim lighting
669	CH	Satisfied		0	0
670	CH	Rather satisfied	A little too dark	General lighting	Dim lighting
671	CH	Satisfied		0	0
672	CH	Rather unsatisfied	There is a small degree of reflection from the right, due to the opening of the blind.	Daylighting	Discomfort glare
673	CH	Satisfied		0	0
674	CH	Satisfied		0	0
675	CH	Satisfied		0	0
676	CH	Satisfied		0	0
677	CH	Satisfied		0	0
678	CH	Satisfied		0	0
679	CH	Satisfied		0	0
680	CH	Rather satisfied	glare on second screen	Computer screen	Reflections
681	CH	Satisfied		0	0
682	CH	Rather satisfied	fond du local (mur) plus lumineux que mon écran ?> contraste	Daylighting	Discomfort glare
683	CH	Satisfied		0	0
684	CH	Satisfied		0	0

ID	Socio-environmental context	Satisfaction with lighting conditions	Answers to OEQ	"What" variable	"Why" variable
685	CH	Rather satisfied	Shutter handle is not on my side of the office, at specific times I have a very strong reflected light in my face	0	0
686	CH	Unsatisfied	Very strong light from window	Daylighting	Discomfort glare
687	CH	Rather satisfied	un peu trop lumineux sur la gauche	Daylighting	Discomfort glare
688	CH	Rather satisfied	lumière sur la gauche un peu trop intense	Daylighting	Discomfort glare
689	CH	Satisfied		0	0
690	CH	Satisfied		0	0
691	CH	Satisfied		0	0
692	CH	Rather satisfied	The light from the open window makes a gradient in the room. I prefer an even lighting.	Daylighting	Type
693	CH	Rather satisfied	un peut d'ombre à cause des rideaux	General lighting	Dim lighting
694	CH	Rather satisfied	rien	0	0
695	CH	Rather satisfied	Depending on the time of the day the sun shines at an angle right at eye-level. The metal screen and blinds must be shut at this time otherwise it causes too much screen glare.	0	0
696	CH	Rather satisfied	Since it is approaching the afternoon, the sunlight is too direct.	Daylighting	Discomfort glare
697	CH	Satisfied		0	0
698	CH	Satisfied		0	0
699	CH	Rather satisfied	Reflections from the outside	Daylighting	Discomfort glare
700	CH	Rather unsatisfied	Outside light	Daylighting	Discomfort glare
701	CH	Satisfied		0	0
702	CH	Rather satisfied	I am sitting too close to the window and the glare on my screen is making me bit uncomfortable	Computer screen	Reflections
703	CH	Rather satisfied	One set of the artificial white lights that are directed into my eyes when on.	0	0
704	CH	Rather unsatisfied	Light too strong from the window	Daylighting	Discomfort glare
705	CH	Satisfied		0	0
706	CH	Satisfied		0	0
707	CH	Rather satisfied	Maybe too much sunlight	Daylighting	Discomfort glare
708	CH	Rather satisfied	Maybe not enough light on the LCD screen, compared to the sunlight	Computer screen	Brightness
709	CH	Satisfied		0	0
710	CH	Satisfied		0	0
711	CH	Rather unsatisfied	Manque de luminosité (pas de lumière naturelle)	Daylighting	Insufficiency
712	CH	Rather unsatisfied	A ma gauche c'est sombre et à ma droite trop de lumière	Daylighting	Discomfort glare
713	CH	Rather satisfied	have to keep blinds down as direct sunlight is too strong in the morning	0	0
714	CH	Rather unsatisfied	glare	Daylighting	Discomfort glare
715	CH	Rather satisfied	you need to pull down the shadings because of the heat but then the room gets too dark in the afternoon.	0	0
716	CH	Rather satisfied	glare on the screen coming from the window, but the room is well-lighten up.	Computer screen	Reflections
717	CH	Satisfied		0	0
718	CH	Unsatisfied		Daylighting	Discomfort glare
719	CH	Satisfied		0	0
720	CH	Rather satisfied	Rien	0	0
721	CH	Unsatisfied	Lumière électrique, sombre	Artificial lighting	Type
722	CH	Unsatisfied	Trop de soleil, éblouissement	Daylighting	Discomfort glare
723	CH	Rather satisfied	Les stores qui se baissent tous les jours automatiquement.	0	0
724	CH	Rather satisfied	La latéralité de la lumière.. elle vient depuis la fenêtre, sur un seul coté	Daylighting	Type
725	CH	Rather satisfied	trop sombre	General lighting	Dim lighting
726	CH	Rather satisfied	rien de particulier	0	0
727	CH	Rather satisfied	luminosité changeante	Daylighting	Type
728	CH	Rather satisfied	luminosité qu'à droite	Daylighting	Discomfort glare
729	CH	Satisfied		0	0
730	CH	Rather satisfied	Les reflets sur le bureau	Daylighting	Discomfort glare
731	CH	Rather unsatisfied	I don't have much natural light throughout the year, it is rather dark and so I have to turn on the artificial light. The artificial light is too artificial to be working under many hours. Also, the blinds come down automatically several times a day and I have to move turn that off several times a day. I am not sure why they come down and when I ask other people in the building people blame the architects.	Daylighting	Insufficiency
732	CH	Rather unsatisfied	There is scaffolding outside my window that prevents natural light from coming in	General lighting	Dim lighting
733	CH	Rather satisfied	Stores baissés à cause de la chaleur	General lighting	Dim lighting
734	CH	Satisfied		0	0
735	CH	Rather unsatisfied	obligation d'allumer les néons toute la journée. Et stores fermés toute la matinée.	Artificial lighting	Type
736	CH	Unsatisfied	soleil	Daylighting	Discomfort glare
737	CH	Rather unsatisfied	Il n'y a pas assez de lumière du jour.	Daylighting	Insufficiency
738	CH	Rather unsatisfied	Pas assez de lumière du jour	Daylighting	Insufficiency
739	CH	Satisfied		0	0
740	CH	Unsatisfied	Il y a trop de soleil	Daylighting	Discomfort glare
741	CH	Rather satisfied	The sun in the afternoon	0	0
742	CH	Rather satisfied	/	0	0
743	CH	Rather satisfied	Mon collègue allume souvent les lumières du bureau. Les néons me font mal aux yeux.	Artificial lighting	Type

ID	Socio-environmental context	Satisfaction with lighting conditions	Answers to OEQ	"What" variable	"Why" variable
744	CH	Rather satisfied	Mon collègue allume souvent les lumières du bureau et les néons me font mal aux yeux.	Artificial lighting	Type
745	CH	Rather satisfied	Éblouissement dû au soleil le matin	0	0
746	CH	Unsatisfied	Trop de lumière sur la place de travail	Daylighting	Discomfort glare
747	CH	Rather satisfied	N/A	0	0
748	CH	Rather satisfied	N/A	0	0
749	CH	Rather satisfied	Rien de particulier	0	0
750	CH	Rather satisfied	Rien de particulier	0	0
751	CH	Satisfied		0	0
752	CH	Satisfied		0	0
753	CH	Rather satisfied	la température	0	0
754	CH	Rather unsatisfied	la température	0	0
755	CH	Satisfied		0	0
756	CH	Rather satisfied	Côté gauche trop lumineux	Daylighting	Discomfort glare
757	CH	Rather satisfied	reflet de la vitre derrière l'écran de l'ordinateur	Computer screen	Reflections
758	CH	Rather unsatisfied	luminosité de la fenêtre	Daylighting	Discomfort glare
759	CH	Rather unsatisfied	obligation d'allumer la lumière même en été	Artificial lighting	Type
760	CH	Rather unsatisfied	bureau trop sombre	General lighting	Dim lighting
761	CH	Rather satisfied	the blinds	0	0
762	CH	Rather satisfied	direct sun light to the window	Daylighting	Discomfort glare
763	CH	Satisfied		0	0
764	CH	Satisfied		0	0
765	CH	Rather satisfied	l'orientation de l'écran	Computer screen	Reflections
766	CH	Rather unsatisfied	Trop de lumière soleil	Daylighting	Discomfort glare
767	CH	Rather satisfied	Un peu trop lumineux	Daylighting	Discomfort glare
768	CH	Rather unsatisfied	Trop lumineux	Daylighting	Discomfort glare
769	CH	Rather satisfied	ca va	0	0
770	CH	Rather satisfied	ecran	Computer screen	Reflections
771	CH	Satisfied		0	0
772	CH	Rather unsatisfied	too much light	Daylighting	Discomfort glare
773	CH	Satisfied		0	0
774	CH	Rather unsatisfied	Trop de soleil direct sur mon bureau, mais il faut que je change l'emplacement de mon bureau du mur droit au mur gauche	Daylighting	Discomfort glare
775	CH	Rather unsatisfied	reflet de lumière sur le bureau	Daylighting	Discomfort glare
776	CH	Unsatisfied	soleil intense et chaleur	Daylighting	Discomfort glare
777	CH	Satisfied		0	0
778	CH	Unsatisfied	Trop de lumière Trop d'ensoleillement Sensation d'éblouissement Sensation de devoir froncer les sourcils	Daylighting	Discomfort glare
779	CH	Satisfied		0	0
780	CH	Rather unsatisfied	Luminosité trop forte	Daylighting	Discomfort glare
781	CH	Rather satisfied	les néons l'après-midi et en hiver	0	0
782	CH	Satisfied		0	0
783	CH	Rather satisfied	Maybe not enough light	General lighting	Dim lighting
784	CH	Satisfied		0	0
785	CH	Rather satisfied	L'instabilité des néons	Artificial lighting	Type
786	CH	Rather satisfied	Le soleil à l'exterieur	Daylighting	Discomfort glare
787	CH	Rather satisfied	could use more direct sunlight	Daylighting	Insufficiency
788	CH	Rather satisfied	a little too bright	Daylighting	Discomfort glare
789	CH	Rather satisfied	Aucun éléments me dérangent, pour le moment.	0	0
790	CH	Satisfied		0	0
791	CH	Rather satisfied	La luminosité venant du dehors, un peu	Daylighting	Discomfort glare
792	CH	Rather unsatisfied	La luminosité provenant du dehors	Daylighting	Discomfort glare
793	CH	Rather unsatisfied	Too much light	Daylighting	Discomfort glare
794	CH	Unsatisfied	Far too much light	Daylighting	Discomfort glare
795	CH	Satisfied		0	0
796	CH	Rather satisfied	Un peu trop lumineux	Daylighting	Discomfort glare
797	CH	Satisfied		0	0
798	CH	Rather satisfied	Trop de lumiere	Daylighting	Discomfort glare
799	CH	Satisfied		0	0
800	CH	Rather unsatisfied	éblouissement dû à la grande fenêtre	Daylighting	Discomfort glare
801	CH	Rather satisfied	trop de luminosité à cause du soleil direct	Daylighting	Discomfort glare
802	CH	Rather satisfied	toujours trop de soleil	Daylighting	Discomfort glare

Appendix B

Questionnaire in English

* After clicking on the buttons "OK, I have understood." and "Next", symbols like the one here under will be shown in the header of a table. Indicate the orientation of the opening (left, right, up, down) of each circle as quickly as possible.



- OK, I have understood.

* Where is the opening of the symbols in the shape of a circle?

	On the left	On the right	Up	Down
				
				
				

* Where is the opening of the symbols in the shape of a circle?

	On the left	On the right	Up	Down
				
				
				

* Where is the opening of the symbols in the shape of a circle?

	On the left	On the right	Up	Down
				

* At the moment, are you satisfied with the lighting conditions in your office?

- Unsatisfied
- Rather unsatisfied
- Rather satisfied
- Satisfied

* Which element(s) bother(s) you in the current lighting conditions?

* How do you like the view through the window at the moment?

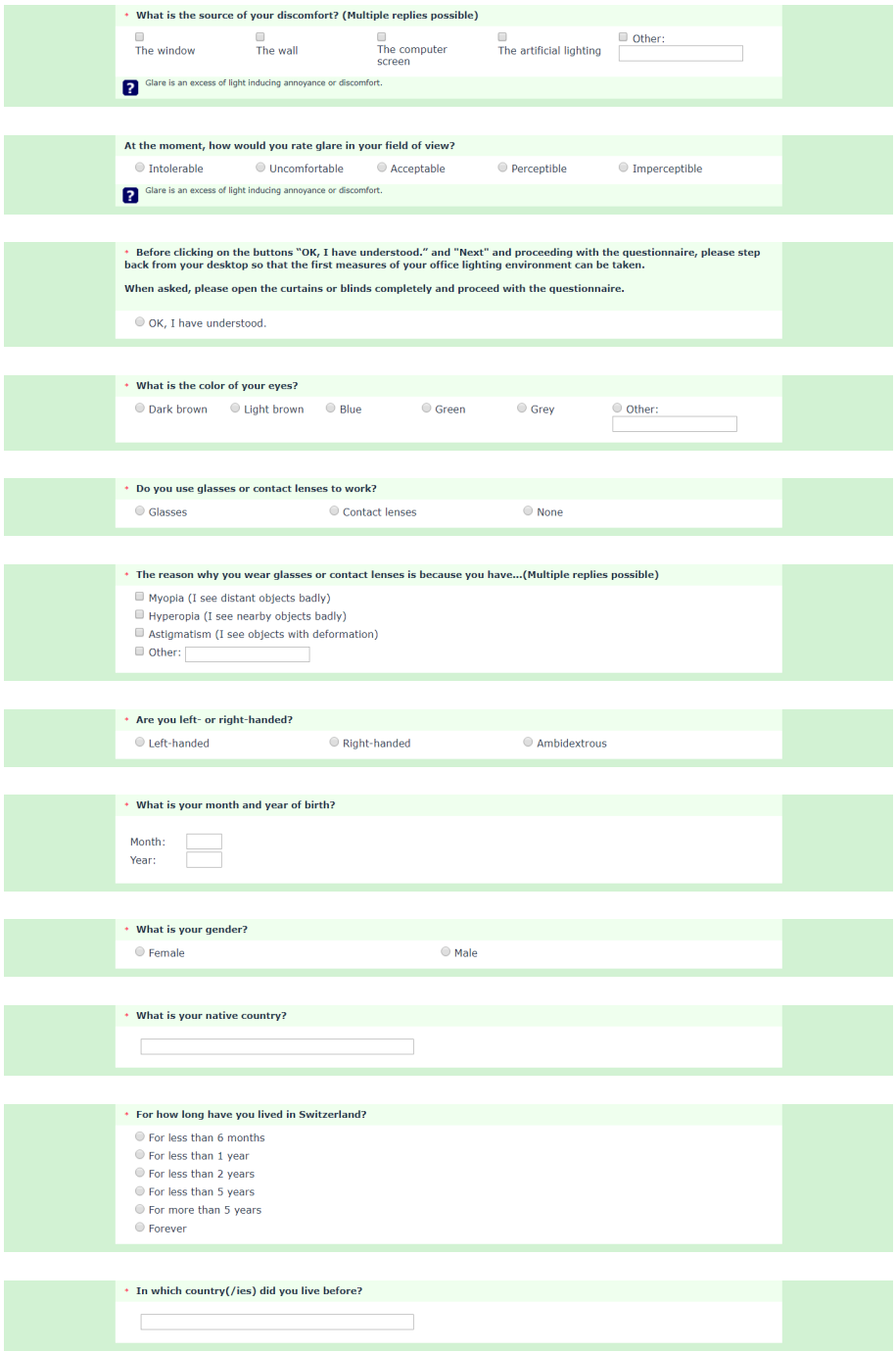
0 10

(0 = ; 10 =)

* At the moment, do you feel discomfort due to glare?

- No, no discomfort
- Yes, a small discomfort
- Yes, a moderate discomfort
- Yes, a large discomfort

Glare is an excess of light inducing annoyance or discomfort.



* What is the source of your discomfort? (Multiple replies possible)

☐ The window ☐ The wall ☐ The computer screen ☐ The artificial lighting ☐ Other:

Glare is an excess of light inducing annoyance or discomfort.

At the moment, how would you rate glare in your field of view?

○ Intolerable ○ Uncomfortable ○ Acceptable ○ Perceptible ○ Imperceptible

Glare is an excess of light inducing annoyance or discomfort.

* Before clicking on the buttons "OK, I have understood." and "Next" and proceeding with the questionnaire, please step back from your desktop so that the first measures of your office lighting environment can be taken.

When asked, please open the curtains or blinds completely and proceed with the questionnaire.

○ OK, I have understood.

* What is the color of your eyes?

○ Dark brown ○ Light brown ○ Blue ○ Green ○ Grey ○ Other:

* Do you use glasses or contact lenses to work?

○ Glasses ○ Contact lenses ○ None

* The reason why you wear glasses or contact lenses is because you have...(Multiple replies possible)

☐ Myopia (I see distant objects badly)
☐ Hyperopia (I see nearby objects badly)
☐ Astigmatism (I see objects with deformation)
☐ Other:

* Are you left- or right-handed?

○ Left-handed ○ Right-handed ○ Ambidextrous

* What is your month and year of birth?

Month:
Year:

* What is your gender?

○ Female ○ Male

* What is your native country?

* For how long have you lived in Switzerland?

○ For less than 6 months
○ For less than 1 year
○ For less than 2 years
○ For less than 5 years
○ For more than 5 years
○ Forever

* In which country(/ies) did you live before?

* How long did you live in this(/these) country(/ies) (in total)?

- Less than 6 months
- Less than 1 year
- Less than 2 years
- Less than 5 years
- More than 5 years

* Do you consider yourself sensitive to glare?

0 (Pas sensible / Not sensitive) — 10 (Très sensible / Very sensitive)

For instance, a frequent use of sunglasses is a sign of sensitivity to glare.

* Do you consider yourself to be more active and alert in the morning or in the afternoon?

Definitely in the morning | Rather in the morning | Rather in the afternoon | Definitely in the afternoon | I don't know

* How would you rate your current mood?



* How would you rate your current fatigue?



* How do you feel physically right now?



* Have you had coffee, tea, or an energy drink since you got up? (Multiple replies possible)

No | Yes, coffee | Yes, tea | Yes, energy drink | Other:

* When did you last drink coffee, tea, or an energy drink?

- Less than 1 hour ago
- Less than 2 hours ago
- Less than 3 hours ago
- More than 3 hours ago

* After clicking on the buttons "OK, I have understood." and "Next", symbols like the one here under will be shown in the header of a table. Indicate the orientation of the opening (left, right, up, down) of each circle as quickly as possible.



OK, I have understood.

* Where is the opening of the symbols in the shape of a circle?

	On the left	On the right	Up	Down
				
				
				

* **Where is the opening of the symbols in the shape of a circle?**

	On the left	On the right	Up	Down
O	○	○	○	○
C	○	○	○	○
O	○	○	○	○
O	○	○	○	○
O	○	○	○	○
C	○	○	○	○

* **Where is the opening of the symbols in the shape of a circle?**

	On the left	On the right	Up	Down
o	○	○	○	○
o	○	○	○	○
o	○	○	○	○
o	○	○	○	○
o	○	○	○	○
o	○	○	○	○

* **How do you like the view through the window at the moment?**

0 10

(0 = ; 10 =)

* **At the moment, are you satisfied with the lighting conditions in your office?**

○ Unsatisfied ○ Rather unsatisfied ○ Rather satisfied ○ Satisfied

* **Which element(s) bother(s) you in the current lighting conditions?**

* **At the moment, do you feel discomfort due to glare?**

○ No, no discomfort ○ Yes, a small discomfort ○ Yes, a moderate discomfort ○ Yes, a large discomfort

Glare is an excess of light inducing annoyance or discomfort.

* **What is the source of your discomfort? (Multiple replies possible)**

☐ The window ☐ The wall ☐ The computer screen ☐ The artificial lighting ☐ Other:

Glare is an excess of light inducing annoyance or discomfort.

At the moment, how would you rate glare in your field of view?

○ Intolerable ○ Uncomfortable ○ Acceptable ○ Perceptible ○ Imperceptible

Glare is an excess of light inducing annoyance or discomfort.

* **At the moment, are you satisfied with the ambient temperature in your office?**

○ Unsatisfied ○ Rather unsatisfied ○ Rather satisfied ○ Satisfied

* **Why are you not completely satisfied with the ambient temperature?**

○ I am very cold ○ I am a bit cold ○ I am a bit warm ○ I am very warm

* **At the moment, how would you rate glare in your field of view?**

○ Imperceptible ○ Noticeable ○ Disturbing ○ Intolerable

Glare is an excess of light inducing annoyance or discomfort.

Appendix C

Questionnaire in Spanish

* **Después de apoyar sobre el botón "Siguiente", se mostrarán símbolos como este en el encabezado de una tabla. Indique la orientación de la apertura de cada círculo (izquierda, derecha, arriba, abajo) lo más rápidamente posible.**



- OK, comprendí.

* **¿Dónde está la apertura de los símbolos en forma de círculo?**

	A la izquierda	A la derecha	Arriba	Abajo
				
				
				

* **¿Dónde está la apertura de los símbolos en forma de círculo?**

	A la izquierda	A la derecha	Arriba	Abajo
				
				

* **¿Dónde está la apertura de los símbolos en forma de círculo?**

	A la izquierda	A la derecha	Arriba	Abajo

* **¿En este momento, está satisfecho(a) con las condiciones de luz en su oficina?**

- Insatisfecho
- Más bien insatisfecho
- Más bien satisfecho
- Satisfecho

* **¿Qué elementos le molestan en las condiciones actuales de iluminación?**

* **¿En este momento, tiene molestias por deslumbramiento?**

- No, ninguna molestia
- Sí, un poco de molestia
- Sí, una molestia moderada
- Sí, una molestia significativa

El deslumbramiento es un exceso de luz molesta.

* **¿De dónde viene la molestia que esté sintiendo?**

- De la ventana
- Del muro
- De la pantalla del computador
- De las lámparas
- Otros :

* **¿En este momento, cómo evalúa el deslumbramiento en su campo de visión?**

○ Insoportable ○ Incómodo ○ Aceptable ○ Perceptible ○ Imperceptible

* **Antes de apoyar sobre el botón "Siguiente" y de continuar con el cuestionario, por favor retroceda de su escritorio con el fin de tomar las primeras medidas de luminosidad de su puesto de trabajo.**

Cuando le indique, por favor abra completamente las cortinas o persianas y vuelva al cuestionario.

○ OK, comprendí.

* **¿De qué color son sus ojos?**

○ Café Oscuro ○ Café Claro ○ Azules ○ Verdes ○ Grises ○ Otros :

* **¿Generalmente utiliza usted lentes ópticos o lentes de contacto para trabajar?**

○ Lentes ópticos ○ Lentes de contacto ○ Ninguno de los dos

* **La razón porque utiliza lentes o lentes de contacto es porque tiene...**

☐ Miopía (veo mal los objetos lejanos)
☐ Presbicia (veo mal los objetos cercanos)
☐ Astigmatismo (veo los objetos con deformación)
☐ Otros :

* **¿Usted es zurdo(a) o diestro(a)?**

○ Zurdo ○ Diestro ○ Ambidiestro

* **¿Cuál es el mes y año de su nacimiento?**

Mes :
Año :

* **¿Cuál es su sexo?**

○ Femenino ○ Masculino

* **¿Cuál es su país de origen?**

País :

* **¿Desde hace cuánto tiempo vive en Chile?**

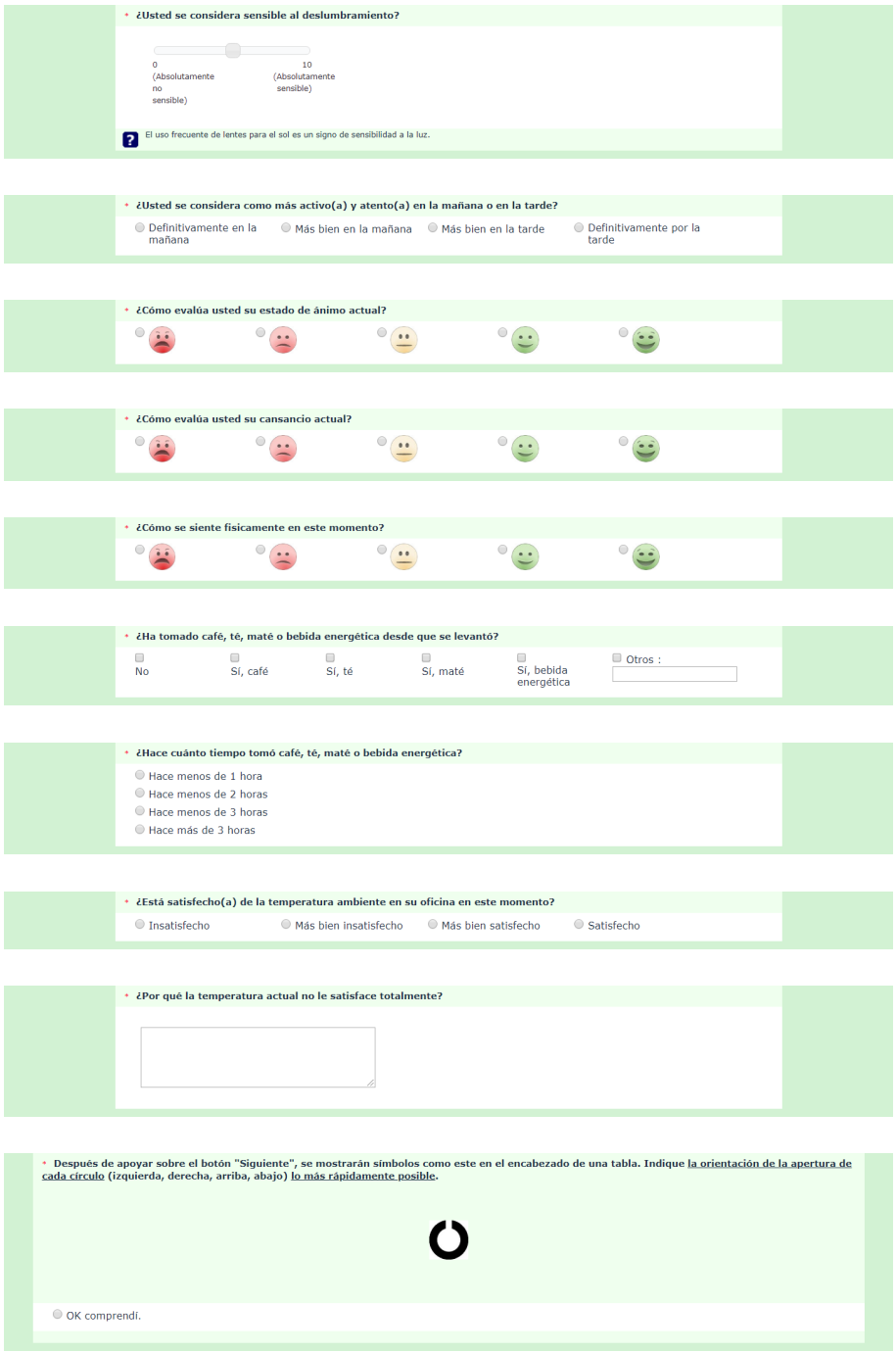
○ Hace menos de 6 meses
○ Hace menos de 1 año
○ Hace menos de 2 años
○ Hace menos de 5 años
○ Hace más de 5 años
○ Toda la vida

* **¿En qué país(es) vivía anteriormente?**

País(es) :

* **¿Durante cuánto tiempo vivió en este(os) país(es) (en total)?**

○ Durante menos de 6 meses
○ Durante menos de 1 año
○ Durante menos de 2 años
○ Durante menos de 5 años
○ Durante más de 5 años



* ¿Usted se considera sensible al deslumbramiento?

0 (Absolutamente no sensible) 10 (Absolutamente sensible)

El uso frecuente de lentes para el sol es un signo de sensibilidad a la luz.

* ¿Usted se considera como más activo(a) y atento(a) en la mañana o en la tarde?

Definitivamente en la mañana | Más bien en la mañana | Más bien en la tarde | Definitivamente por la tarde

* ¿Cómo evalúa usted su estado de ánimo actual?

* ¿Cómo evalúa usted su cansancio actual?

* ¿Cómo se siente fisicamente en este momento?

* ¿Ha tomado café, té, maté o bebida energética desde que se levantó?

No | Sí, café | Sí, té | Sí, maté | Sí, bebida energética | Otros :

* ¿Hace cuánto tiempo tomó café, té, maté o bebida energética?

Hace menos de 1 hora
Hace menos de 2 horas
Hace menos de 3 horas
Hace más de 3 horas

* ¿Está satisfecho(a) de la temperatura ambiente en su oficina en este momento?

Insatisfecho | Más bien insatisfecho | Más bien satisfecho | Satisfecho

* ¿Por qué la temperatura actual no le satisface totalmente?

* Después de apoyar sobre el botón "Siguiente", se mostrarán símbolos como este en el encabezado de una tabla. Indique la orientación de la apertura de cada círculo (izquierda, derecha, arriba, abajo) lo más rápidamente posible.

OK comprendí.

* ¿Dónde está la apertura de los símbolos en forma de círculo?

	A la izquierda	A la derecha	Arriba	Abajo
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○

* ¿Dónde está la apertura de los símbolos en forma de círculo?

	A la izquierda	A la derecha	Arriba	Abajo
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○

* ¿Dónde está la apertura de los símbolos en forma de círculo?

	A la izquierda	A la derecha	Arriba	Abajo
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○

* ¿De su puesto de trabajo, tiene vista a una ventana dando al exterior?

○ Sí ○ Sí, pero la vista por la ventana está bloqueada ○ No, no hay ventana

* ¿Cómo califica en una escala de 0 a 10 la vista por la ventana?

0 10

(0 = ; 10 =)

* ¿Sentado(a) en su escritorio, qué elemento(s) del paisaje puede ver?

☐ El cielo ☐ El suelo ☐ El paisaje a la distancia ☐ Los edificios vecinos ☐ Otros :

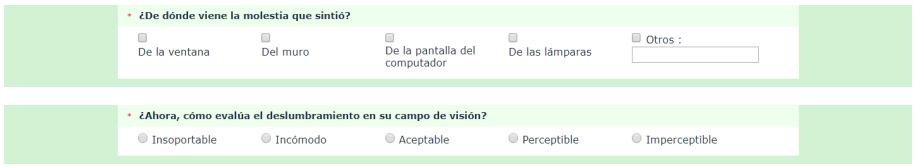
* ¿En este momento, está satisfecho(a) con las condiciones de luz en su oficina?

○ Insatisfecho ○ Más bien insatisfecho ○ Más bien satisfecho ○ Satisfecho

* ¿Qué elementos le molestan en las condiciones actuales de iluminación?

* ¿Durante el tiempo en que completó este cuestionario, sintió molestias por deslumbramiento?

○ No, ninguna molestia ○ Sí, un poco de molestia ○ Sí, una molestia moderada ○ Sí, una molestia significativa


¿De dónde viene la molestia que sintió?
De la ventana
Del muro
De la pantalla del computador
De las lámparas
Otros :
¿Ahora, cómo evalúa el deslumbramiento en su campo de visión?
Insoportable
Incómodo
Aceptable
Perceptible
Imperceptible

Appendix D

Questionnaire in French

* Après avoir appuyé sur les boutons "Ok, j'ai compris." et "Suivant", des symboles tels que celui ci-dessous vont s'afficher en tête de colonne d'un tableau. Il vous est demandé d'indiquer l'orientation de l'ouverture de chaque cercle (gauche, droite, haut, bas) le plus rapidement possible.



OK, j'ai compris.

* Où se trouve l'ouverture des symboles en forme de cercle ?

	À gauche	À droite	En haut	En bas
				
				
				

* Où se trouve l'ouverture des symboles en forme de cercle ?

	À gauche	À droite	En haut	En bas
				
				
				

* Où se trouve l'ouverture des symboles en forme de cercle ?

	À gauche	À droite	En haut	En bas

* En ce moment, êtes-vous satisfait(e) des conditions lumineuses dans votre bureau ?

Insatisfait | Plutôt insatisfait | Plutôt satisfait | Satisfait

* Quel(s) élément(s) vous dérange(nt) dans les conditions lumineuses actuelles ?

* Appréciez-vous la vue que vous avez par la fenêtre en ce moment?

0 10

(0 = ; 10 =)

* En ce moment, ressentez-vous une gêne dûe à l'éblouissement ?

Non, pas de gêne | Oui, une faible gêne | Oui, une gêne modérée | Oui, une gêne importante

L'éblouissement est un excès de lumière gênante.

* **D'où provient la gêne ressentie ? (Plusieurs réponses possibles)**

☐ De la fenêtre ☐ Du mur ☐ De l'écran d'ordinateur ☐ Des lampes ☐ Autre :

? L'éblouissement est un excès de lumière gênante.

* **En ce moment, comment évalueriez-vous l'éblouissement dans votre champ de vision ?**

○ Insupportable ○ Inconfortable ○ Acceptable ○ Perceptible ○ Imperceptible

? L'éblouissement est un excès de lumière gênante.

* **Avant d'appuyer sur les boutons "OK, j'ai compris." et "Suivant" et de continuer le questionnaire, veuillez s'il vous plait reculer de votre bureau afin que les premières mesures de l'environnement lumineux de votre bureau soient effectuées.**

Quand il vous le sera demandé, veuillez s'il vous plait ouvrir complètement les stores et/ou autres protections solaires et continuer le questionnaire.

○ OK, j'ai compris.

* **De quelle couleur sont vos yeux ?**

○ Brun ○ Noisette ○ Bleu ○ Vert ○ Gris ○ Autre :

* **Portez-vous généralement des lunettes ou lentilles de contact pour travailler ?**

○ Lunettes ○ Lentilles de contact ○ Aucun des deux

* **La raison pour laquelle vous portez des lunettes ou lentilles de contact est que vous êtes... (Plusieurs réponses possibles)**

☐ Myope (je vois flou les objets lointains)
☐ Presbyte (je vois flou les objets proches)
☐ Astigmate (je vois les objets déformés)
☐ Autre :

* **Êtes-vous gaucher ou droitier ?**

○ Gaucher ○ Droitier ○ Ambidextre

* **Quel est votre mois et année de naissance ?**

Mois :
Année :

* **Quel est votre sexe ?**

○ Féminin ○ Masculin

* **Quel est votre pays d'origine ?**

* **Depuis combien de temps vivez-vous en Belgique ?**

○ Depuis moins de 6 mois
○ Depuis moins d'1 an
○ Depuis moins de 2 ans
○ Depuis moins de 5 ans
○ Depuis plus de 5 ans
○ Depuis toujours

* **Dans quel(s) pays avez-vous vécu précédemment ?**

* **Pendant combien de temps avez-vous vécu dans ce(s) pays (au total) ?**

- Pendant moins de 6 mois
- Pendant moins d'1 an
- Pendant moins de 2 ans
- Pendant moins de 5 ans
- Pendant plus de 5 ans

* **Vous considérez-vous comme étant sensible à l'éblouissement ?**

0 (Pas sensible) — 10 (Très sensible)

? Le port fréquent de lunettes de soleil est un signe de sensibilité à l'éblouissement.

* **Vous considérez-vous comme étant plus actif(/ve) et alerte le matin ou l'après-midi ?**

Le matin | Plutôt le matin | Plutôt l'après-midi | L'après-midi | Je ne sais pas

* **Comment évaluez-vous votre humeur actuelle ?**



* **Comment évaluez-vous votre fatigue actuelle ?**



* **Comment évaluez-vous votre état physique actuel ?**



* **Avez-vous bu du café, thé ou une boisson énergisante depuis votre réveil ? (Plusieurs réponses possibles)**

☐ Non | ☐ Oui, du café | ☐ Oui, du thé | ☐ Oui, une boisson énergisante | ☐ Autre :

* **Quand avez-vous bu pour la dernière fois un/une café/thé/boisson énergisante ?**

- Il y a moins d'1 heure
- Il y a moins de 2 heures
- Il y a moins de 3 heures
- Il y a plus de 3 heures

* **Êtes-vous satisfait(e) de la température ambiante de votre bureau en ce moment ?**

Insatisfait | Plutôt insatisfait | Plutôt satisfait | Satisfait

* **Pourquoi la température ambiante actuelle ne vous satisfait-elle pas totalement ?**

J'ai très froid | J'ai un peu froid | J'ai un peu chaud | J'ai très chaud

* **Après avoir appuyé sur les boutons "Ok, j'ai compris." et "Suivant", des symboles tels que celui ci-dessous vont s'afficher en tête de colonne d'un tableau. Il vous est demandé d'indiquer l'orientation de l'ouverture de chaque cercle (gauche, droite, haut, bas) le plus rapidement possible.**



- OK, j'ai compris.

* **Où se trouve l'ouverture des symboles en forme de cercle ?**

	À gauche	À droite	En haut	En bas
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○

* **Où se trouve l'ouverture des symboles en forme de cercle ?**

	À gauche	À droite	En haut	En bas
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○

* **Où se trouve l'ouverture des symboles en forme de cercle ?**

	À gauche	À droite	En haut	En bas
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○

* **Appréciez-vous la vue que vous avez par la fenêtre en ce moment?**

0 10

(0 = ; 10 =)

* **En ce moment, êtes-vous satisfait(e) des conditions lumineuses dans votre bureau ?**

○ Insatisfait ○ Plutôt insatisfait ○ Plutôt satisfait ○ Satisfait

* **Quel(s) élément(s) vous dérange(nt) dans les conditions lumineuses actuelles ?**

* **En ce moment, ressentez-vous une gêne dûe à l'éblouissement ?**

○ Non, pas de gêne ○ Oui, une faible gêne ○ Oui, une gêne modérée ○ Oui, une gêne importante

L'éblouissement est un excès de lumière gênante.

* **D'où provient la gêne ressentie ? (Plusieurs réponses possibles)**

☐ De la fenêtre ☐ Du mur ☐ De l'écran d'ordinateur ☐ Des lampes ☐ Autre :

L'éblouissement est un excès de lumière gênante.

* **En ce moment, comment évalueriez-vous l'éblouissement dans votre champ de vision ?**

○ Insupportable ○ Inconfortable ○ Acceptable ○ Perceptible ○ Imperceptible

L'éblouissement est un excès de lumière gênante.

Appendix E

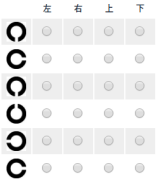
Questionnaire in Japanese

* 「了解しました」「次」のボタンをクリックした後、下にあるような記号が表の見出しに出てきます。各円の開いている方向（左、右、上、下）をできる限り早く示してください。



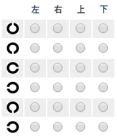
○ わかりました。

* 円の開いている部分はどこにありますか？



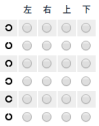
	左	右	上	下
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○

* 円の開いている部分はどこにありますか？



	左	右	上	下
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○

* 円の開いている部分はどこにありますか？



	左	右	上	下
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○
C	○	○	○	○

* 現在、あなたはオフィスの光環境に満足していますか？

○ 不満　○ どちらかといえば不満　○ どちらかといえば満足　○ 満足

* 現在の光環境で、何か問題がありますか？

* 現在、グレアによる不快感を感じますか？

○ いいえ、不快ではありません。　○ はい、少し不快です。　○ はい、ある程度不快です。　○ はい、とても不快です。

? ここでいう「グレア」とは不快感を引き起こす過剰な光のことです。

* あなたのグレアの原因は何ですか？（複数回答可）

☐ 窓　☐ 壁　☐ パソコンの画面　☐ 人工照明　☐ その他：

? ここでいう「グレア」とは不快感を引き起こす過剰な光のことです。

現在、あなたの視野内のグレアをどの程度だと評価しますか？

○ 耐え難い　○ 不快である　○ 許容範囲である　○ 感じる程度である　○ 感じない

ここでいう「グレア」とは不快感を引き起こす過剰な光のことです。

* 現在、窓から見える景色が好きですか？

0　10

(0 = ；10 =)

* 現在、あなたの視野内のグレアをどの程度だと評価しますか？

○ 感じない　○ 感じる程度である　○ 邪魔である　○ 耐え難い

ここでいう「グレア」とは不快感を引き起こす過剰な光のことです。

* 「了解しました」「次」ボタンをクリックしアンケートを進める前に、オフィスの光環境の計測を行いますので、机から一歩下がってください。

指示が出たら、カーテン、ブラインドあるいはその他のこれに類するものを完全に開いてアンケートを再開してください。

○ わかりました。

* あなたの目の色は何ですか？

○ 暗い茶色　○ 明るい茶色　○ 青　○ 緑　○ 灰色　○ その他：

* メガネやコンタクトレンズを仕事の時に使いますか？

○ メガネ　○ コンタクトレンズ　○ 使わない

* メガネやコンタクトレンズを使う理由は何ですか？（複数回答可）

☐ 近視 (遠くのものがぼやけて見える)
☐ 遠視(近くのものがぼやけて見える)
☐ 乱視(ものが歪んで見える)
☐ その他：

* あなたは左利きですか？右利きですか？

○ 左利き　○ 右利き　○ 両利き

* あなたの誕生月と誕生年はいつですか？西暦でお答えください。

月
年

* あなたの性別は？

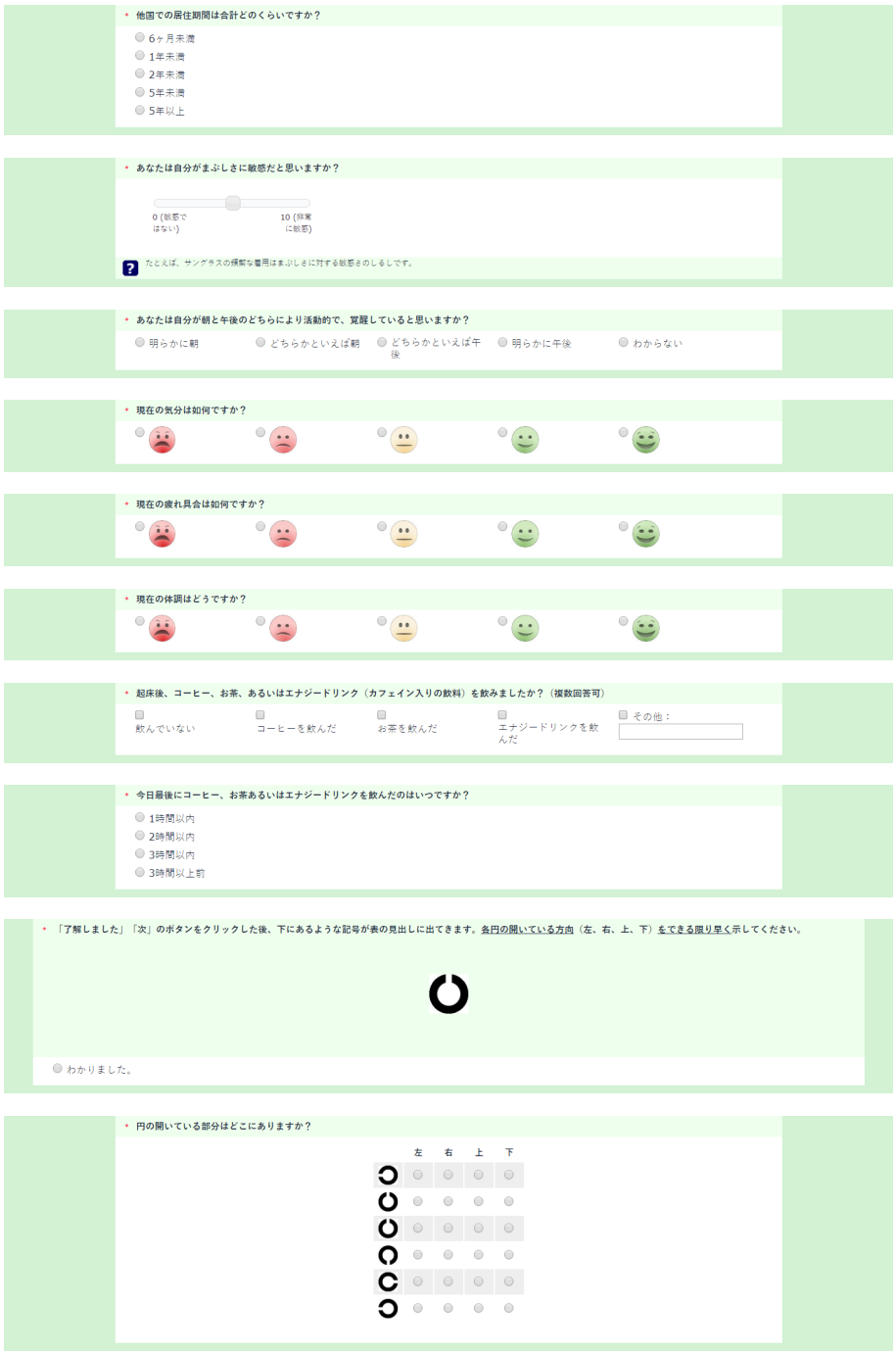
○ 女性　○ 男性

* あなたの出生国はどこですか？

* 日本に住んでどのくらいになりますか？

○ 6ヶ月未満
○ 1年未満
○ 2年未満
○ 5年未満
○ 5年以上
○ 生まれてからずっと

* 過去にどの国に居住したことがありますか（複数記述可）？



* 他国での居住期間は合計どのくらいですか？
- 6ヶ月未満
- 1年未満
- 2年未満
- 5年未満
- 5年以上

* あなたは自分がまぶしさに敏感だと思いますか？

0 (敏感ではない) 10 (非常に敏感)

? たとえば、サングラスの頻繁な着用はまぶしさに対する敏感さのしるしです。

* あなたは自分が朝と午後のどちらにより活動的で、覚醒していると思いますか？

明らかに朝 | どちらかといえば朝 | どちらかといえば午後 | 明らかに午後 | わからない

* 現在の気分は如何ですか？

* 現在の疲れ具合は如何ですか？

* 現在の体調はどうですか？

* 起床後、コーヒー、お茶、あるいはエナジードリンク（カフェイン入りの飲料）を飲みましたか？（複数回答可）

飲んでいない | コーヒーを飲んだ | お茶を飲んだ | エナジードリンクを飲んだ | その他：

* 今日最後にコーヒー、お茶あるいはエナジードリンクを飲んだのはいつですか？
- 1時間以内
- 2時間以内
- 3時間以内
- 3時間以上前

* 「了解しました」「次」のボタンをクリックした後、下にあるような記号が表の見出しに出てきます。各円の開いている方向（左、右、上、下）をできる限り早く示してください。

- わかりました。

* 円の開いている部分はどこにありますか？

	左	右	上	下
C				
C				
C				
C				
C				
C				

* 円の開いている部分はどこにありますか？

	左	右	上	下
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○

* 円の開いている部分はどこにありますか？

	左	右	上	下
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○

* 現在、窓から見える景色が好きですか？

0 10

(0 = ; 10 =)

* 現在、あなたはオフィスの光環境に満足していますか？

○ 不満　○ どちらかといえば不満　○ どちらかといえば満足　○ 満足

* 現在の光環境で、何か問題がありますか？

* 現在、グレアによる不快感を感じますか？

○ いいえ、不快ではありません。　○ はい、少し不快です。　○ はい、ある程度不快です。　○ はい、とても不快です。

ここでいう「グレア」とは不快感を引き起こす過剰な光のことです。

* あなたのグレアの原因は何ですか？（複数回答可）

□ 窓　□ 壁　□ パソコンの画面　□ 人工照明　□ その他：

ここでいう「グレア」とは不快感を引き起こす過剰な光のことです。

現在、あなたの視野内のグレアをどの程度だと評価しますか？

○ 耐え難い　○ 不快である　○ 許容範囲である　○ 感じる程度である　○ 感じない

ここでいう「グレア」とは不快感を引き起こす過剰な光のことです。

* 現在、あなたのオフィスの室温に満足していますか？

○ 不満　○ どちらかといえば不満　○ どちらかといえば満足　○ 満足

* なぜ室温に対して完全に満足していないのですか？

○ 非常に寒いから　○ 少し寒いから　○ 少し暑いから　○ 非常に暑いから

* 現在、あなたの視野内のグレアをどの程度だと評価しますか？

○ 感じない　○ 感じる程度である　○ 邪魔である　○ 耐え難い

ここでいう「グレア」とは不快感を引き起こす過剰な光のことです。

Appendix F

Transcript of the Explanatory Video in English

Hello, My name is Clotilde.

I am a PhD student in engineering sciences at UCL, in Belgium.

I am here today because I am currently conducting a study on the differences in visual comfort perceptions of people coming from different cultures. For example, it is believed that Asian people are less sensitive to glare than European people.

Therefore, I run the same experiment in Belgium, Chile, Japan, and Switzerland to compare visual perceptions in each of these four countries. If you agree to participate in this study, you will be asked to fill out a survey that will last a maximum of 15 minutes.

The survey consists of an electronic questionnaire which I will send to you by email.

Once you have answered the first few questions, you will be asked in the questionnaire to leave your desk for about 3 minutes so that I can take the first lighting measurements at your desk.

It is important that you stay out of the field of view of the camera during these 3 minutes.

Next, if you use blinds, curtains or any other shading devices, you will have to open them completely and turn off any sources of artificial light, such as your desk lamp.

You will then be allowed to return to your desk and proceed with the questionnaire.

At the end of the questionnaire, you will be asked a second time to leave your desk so that a second series of lighting measurements can be conducted.

If you are willing to participate in, could you please fill out the consent form with your name, email address, and signature?

All data collected will be treated confidentially and the email address will only be used for sending the questionnaire.

Your participation in this survey is greatly appreciated and will be extremely valuable for my PhD thesis.

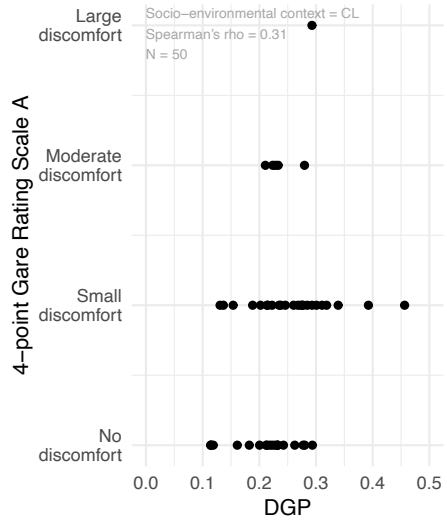
If you have any further question, do not hesitate to ask me.

Thank you!

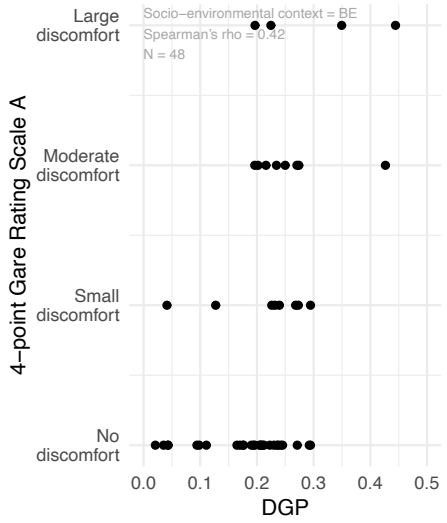
Appendix G

Additional Material from the Statistical Analyses

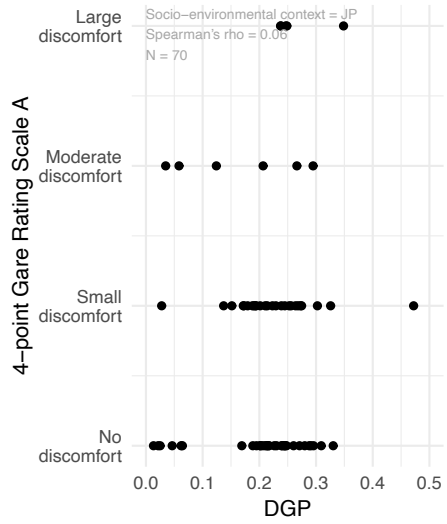
G.1 Graphs from Subsection 6.3.1 in Chapter 6



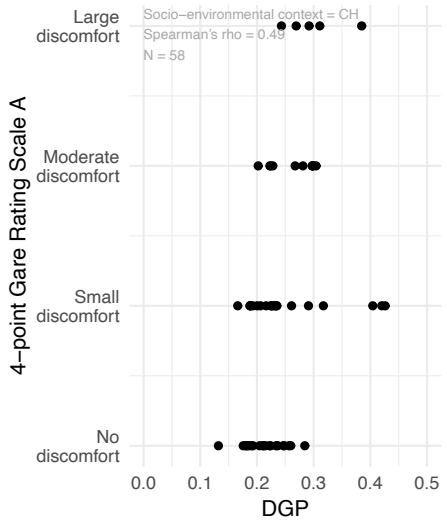
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context

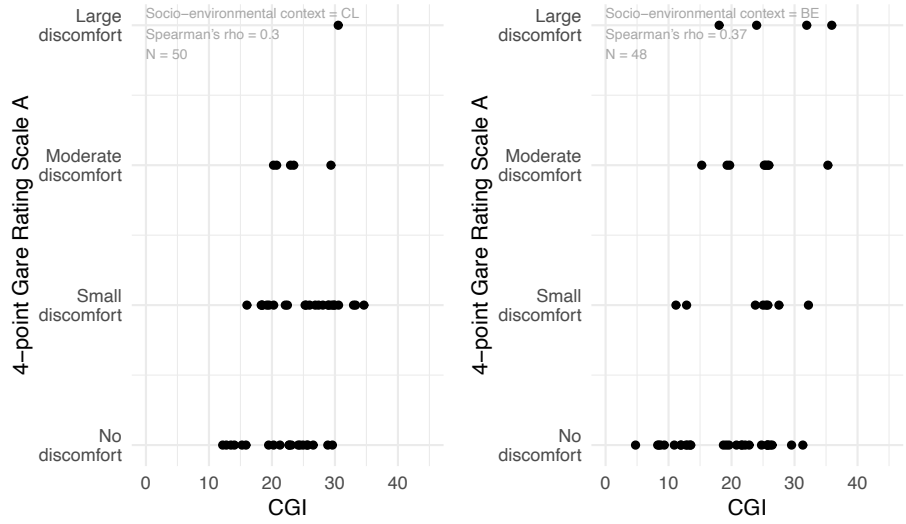


(c) Japanese socio-environmental context



(d) Swiss socio-environmental context

Figure G.1: Scatter plots of the ratings on the 4-point glare rating scale A in function of the DGP values for the four socio-environmental groups



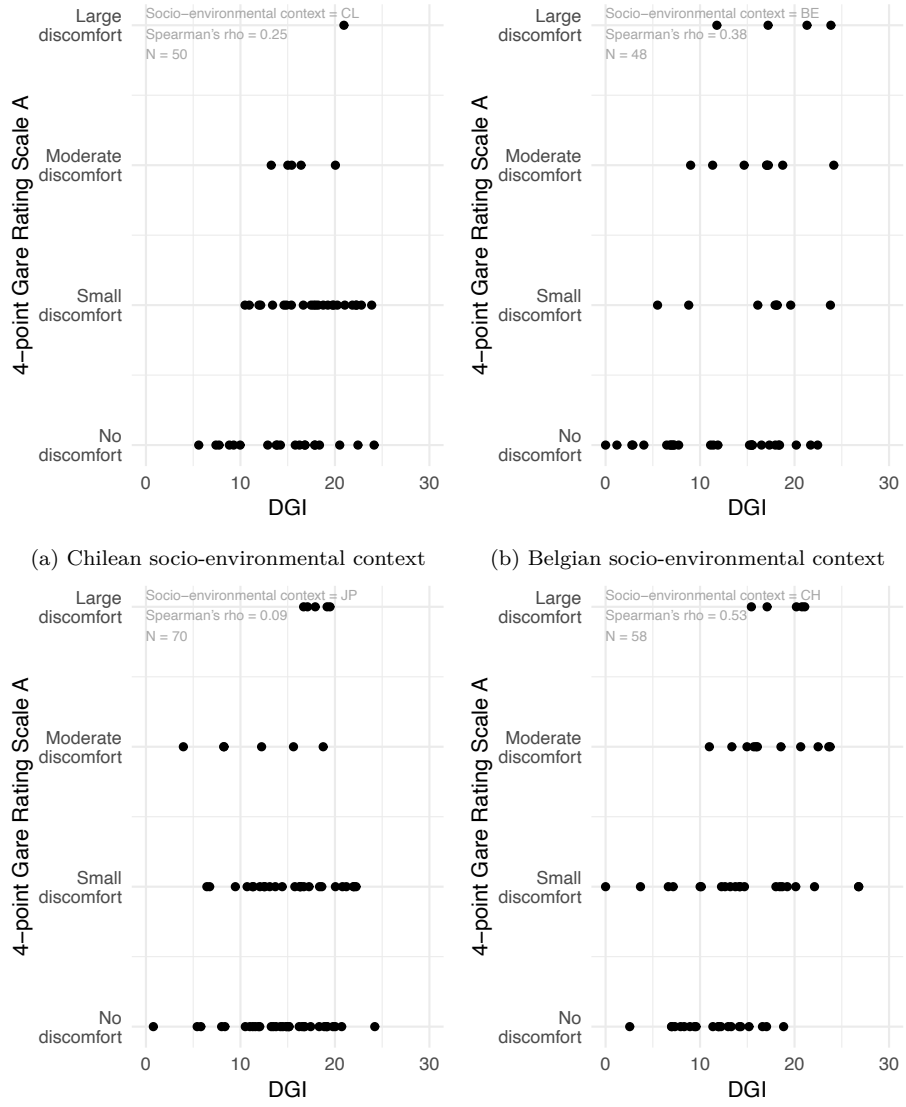
(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

Figure G.2: Scatter plots of the ratings on the 4-point glare rating scale A in function of the CGI values for the four socio-environmental groups



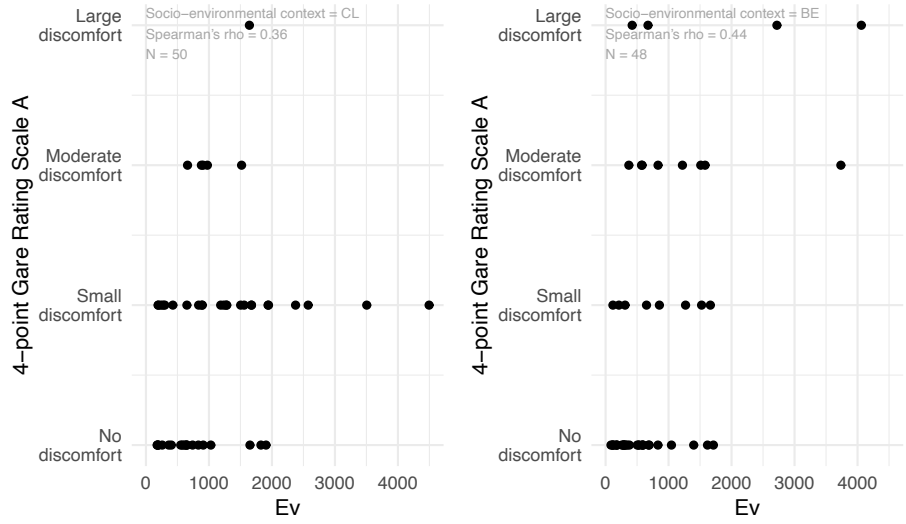
(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

Figure G.3: Scatter plots of the ratings on the 4-point glare rating scale A in function of the DGI values for the four socio-environmental groups



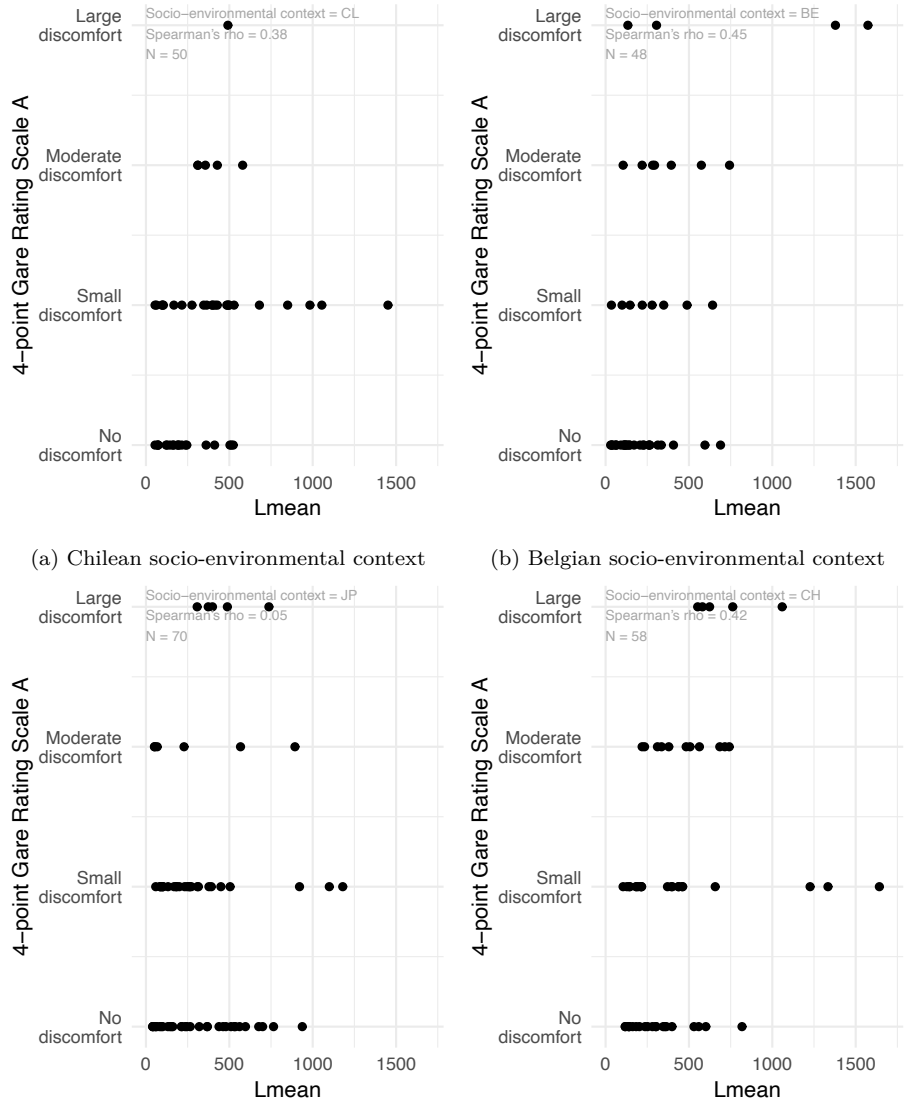
(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

Figure G.4: Scatter plots of the ratings on the 4-point glare rating scale A in function of the E_v values for the four socio-environmental groups



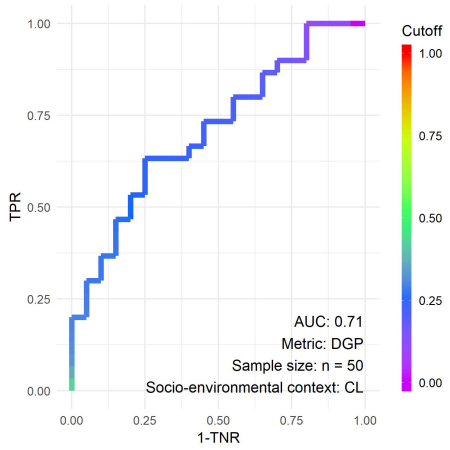
(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

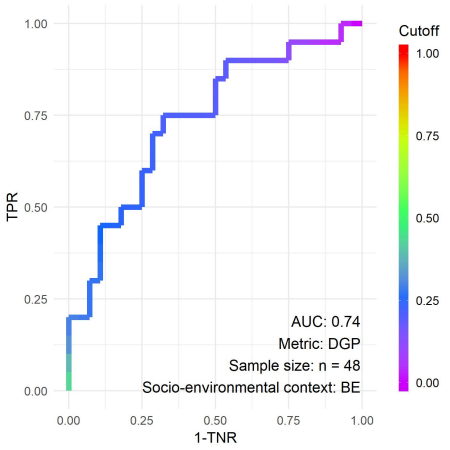
(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

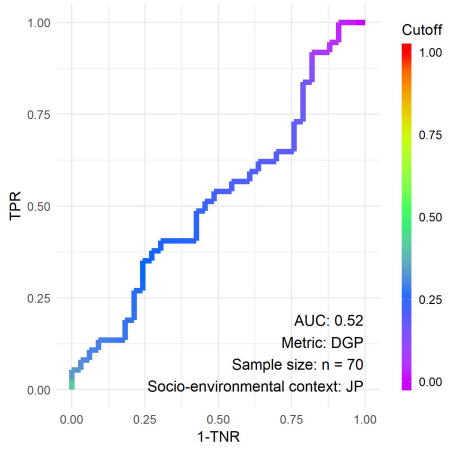
Figure G.5: Scatter plots of the ratings on the 4-point glare rating scale A in function of the L_{mean} values for the four socio-environmental groups



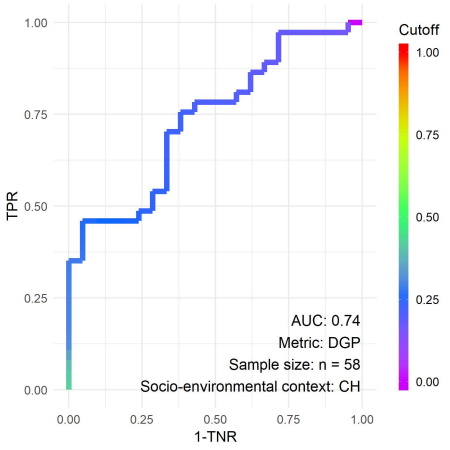
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context

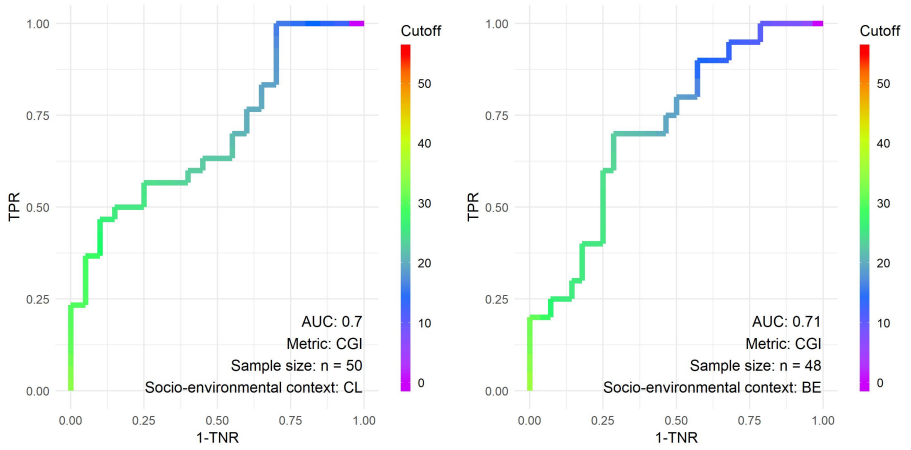


(c) Japanese socio-environmental context



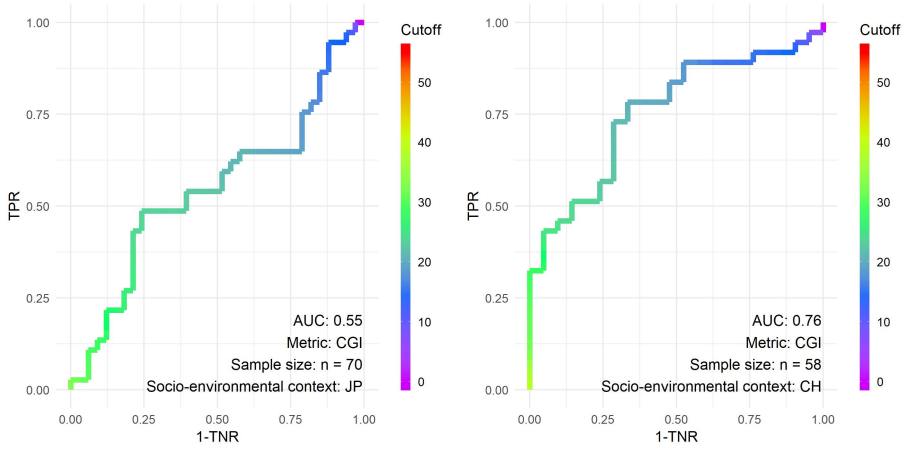
(d) Swiss socio-environmental context

Figure G.6: ROC curves from the analyses of the performance of the DGP to predict the binary transformation of the ratings on the 4-point glare rating scale A in the four socio-environmental groups



(a) Chilean socio-environmental context

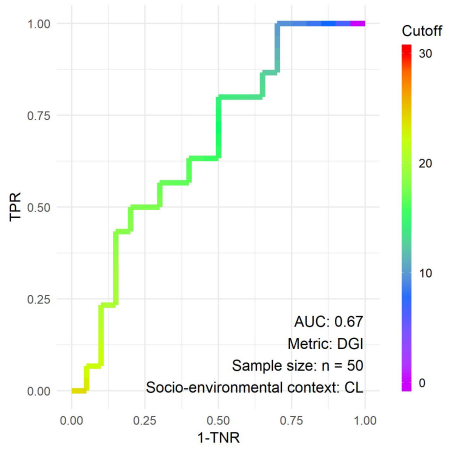
(b) Belgian socio-environmental context



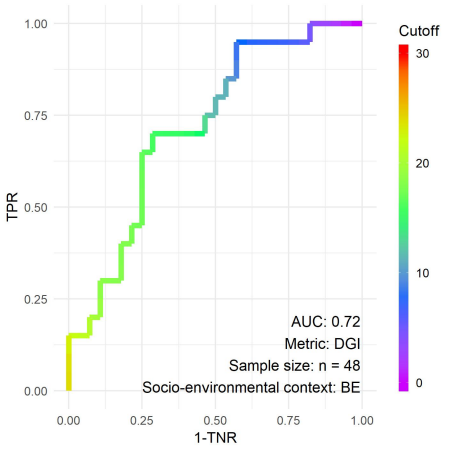
(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

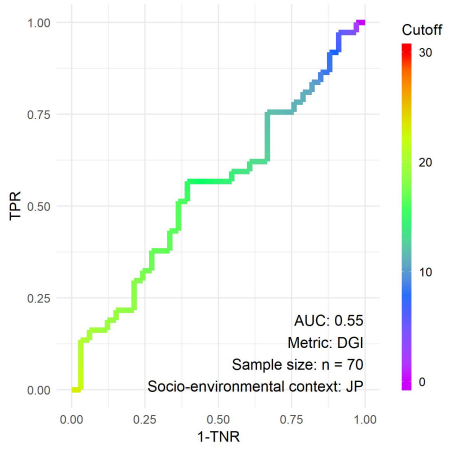
Figure G.7: ROC curves from the analyses of the performance of the CGI to predict the binary transformation of the ratings on the 4-point glare rating scale A in the four socio-environmental groups



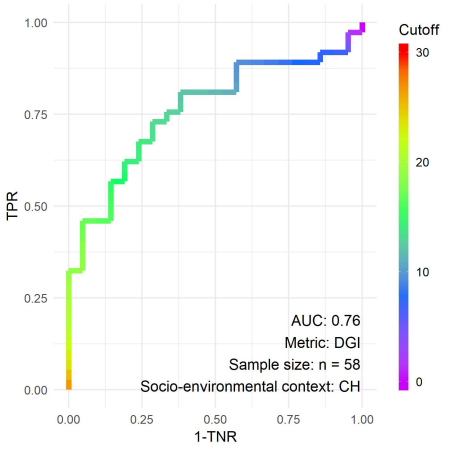
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context

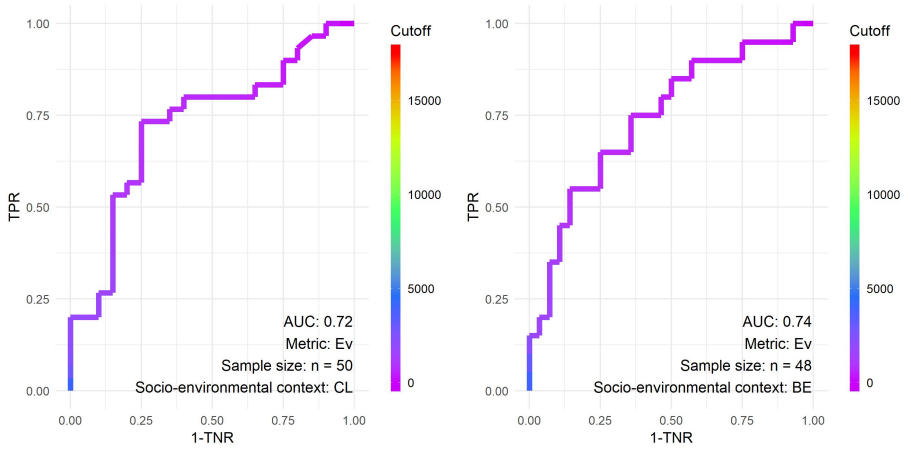


(c) Japanese socio-environmental context



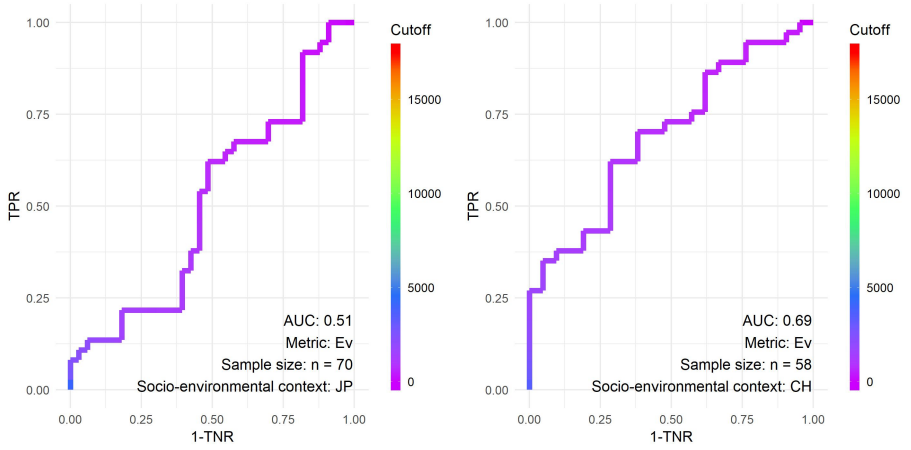
(d) Swiss socio-environmental context

Figure G.8: ROC curves from the analyses of the performance of the DGI to predict the binary transformation of the ratings on the 4-point glare rating scale A in the four socio-environmental groups



(a) Chilean socio-environmental context

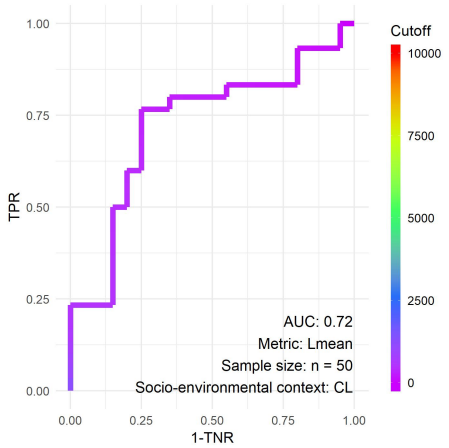
(b) Belgian socio-environmental context



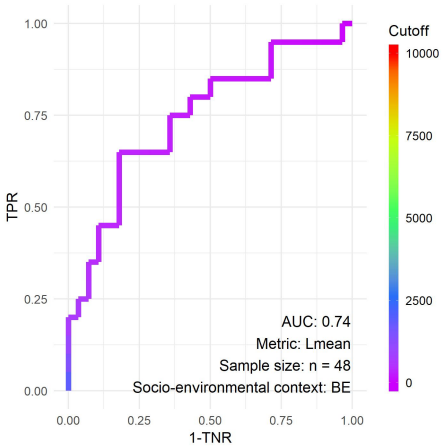
(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

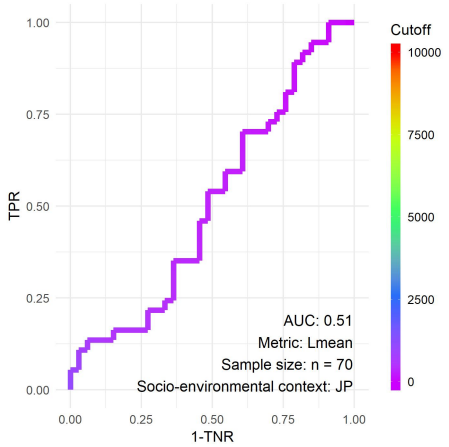
Figure G.9: ROC curves from the analyses of the performance of the E_v to predict the binary transformation of the ratings on the 4-point glare rating scale A in the four socio-environmental groups



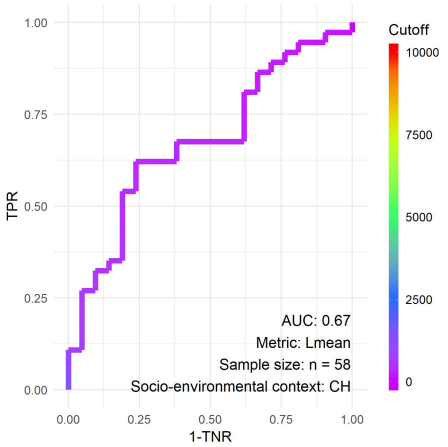
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context



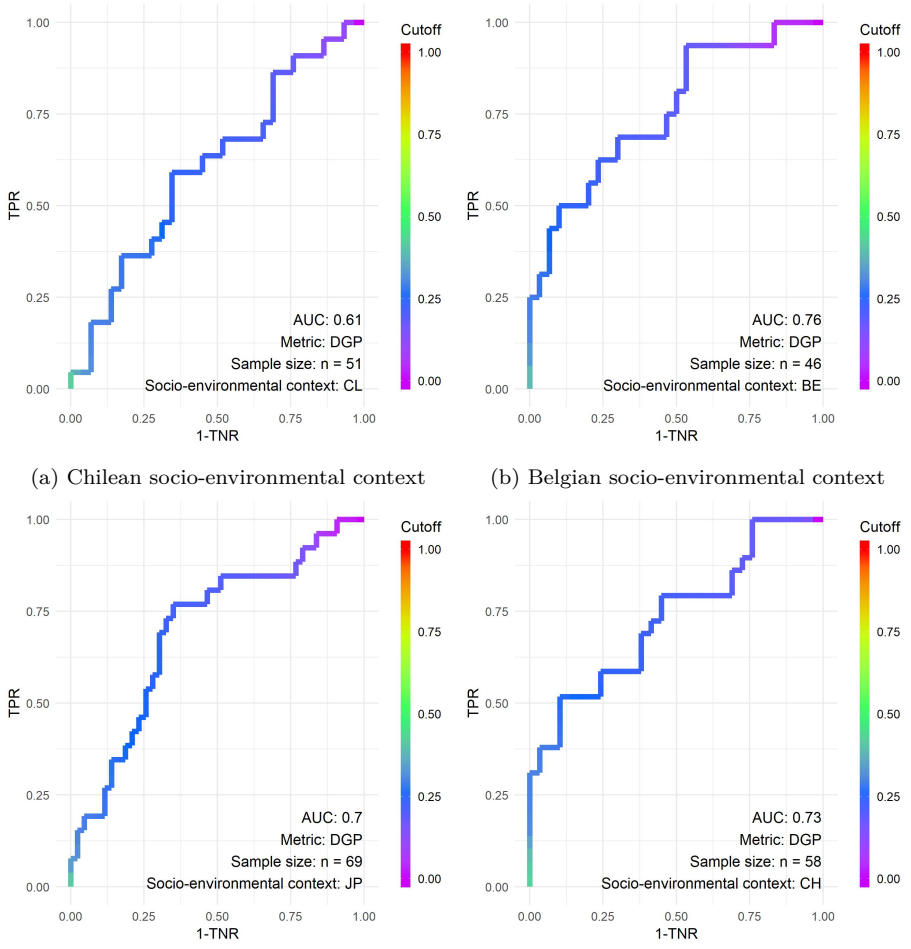
(c) Japanese socio-environmental context



(d) Swiss socio-environmental context

Figure G.10: ROC curves from the analyses of the performance of the L_{mean} to predict the binary transformation of the ratings on the 4-point glare rating scale A in the four socio-environmental groups

G.2 Graphs from Subsection 6.4.1 in Chapter 6



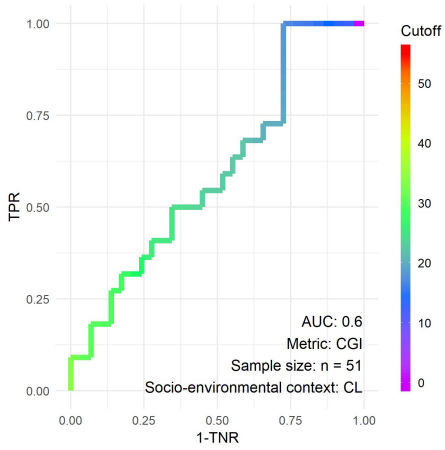
(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

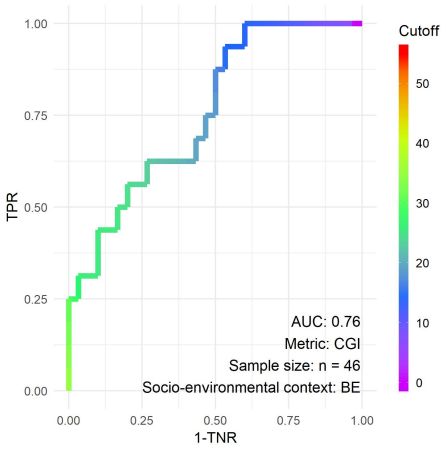
(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

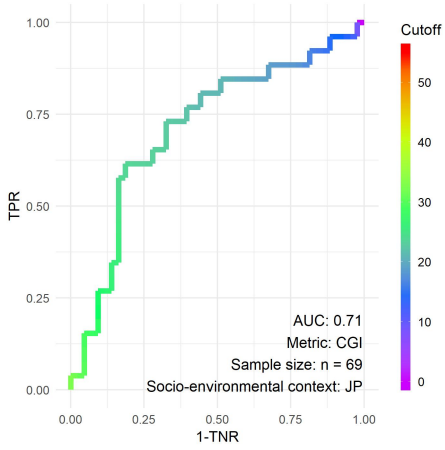
Figure G.11: ROC curves from the analyses of the performance of the DGP to predict the binary glare report in the four socio-environmental groups



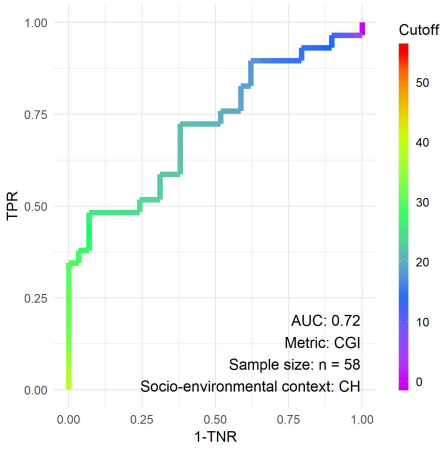
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context

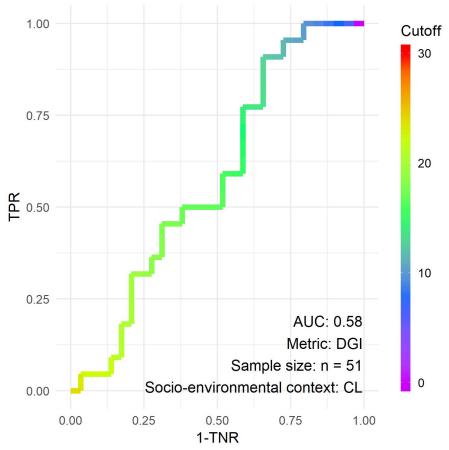


(c) Japanese socio-environmental context

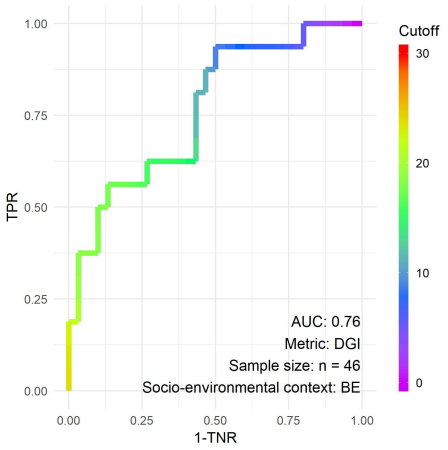


(d) Swiss socio-environmental context

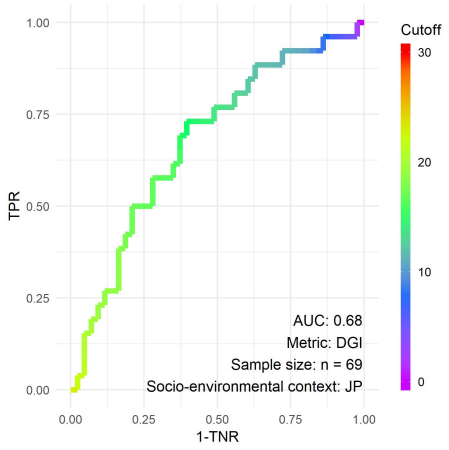
Figure G.12: ROC curves from the analyses of the performance of the CGI to predict the binary glare report in the four socio-environmental groups



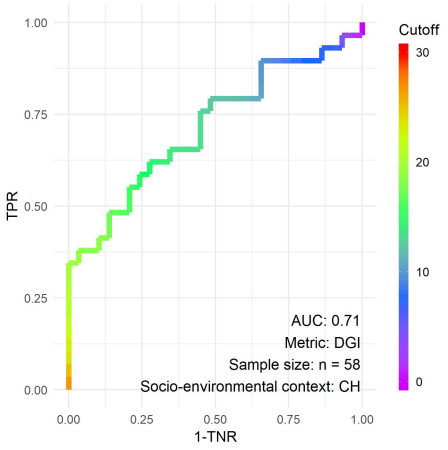
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context

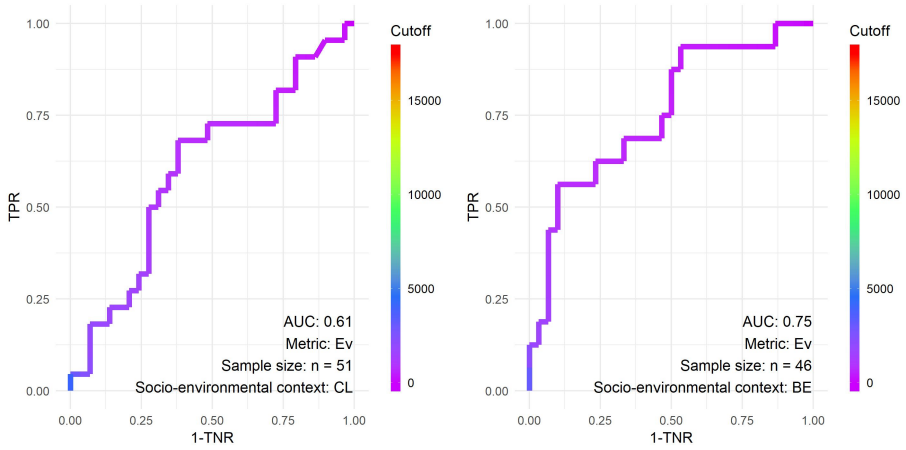


(c) Japanese socio-environmental context



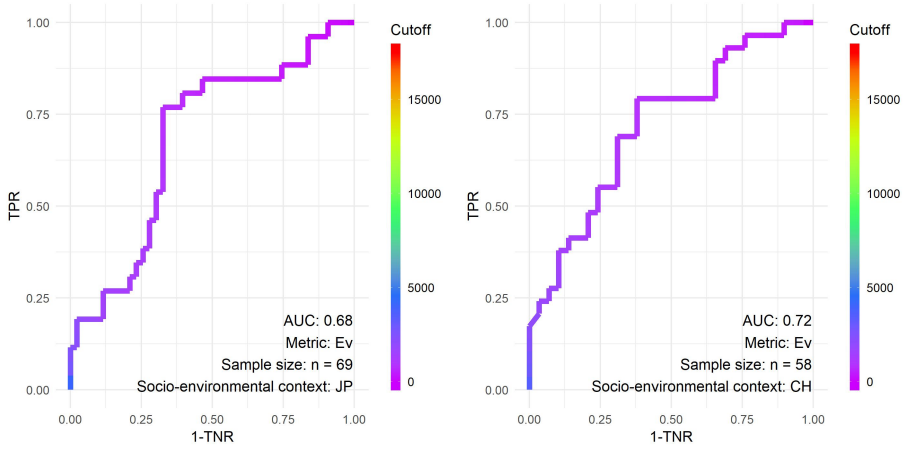
(d) Swiss socio-environmental context

Figure G.13: ROC curves from the analyses of the performance of the DGI to predict the binary glare report in the four socio-environmental groups



(a) Chilean socio-environmental context

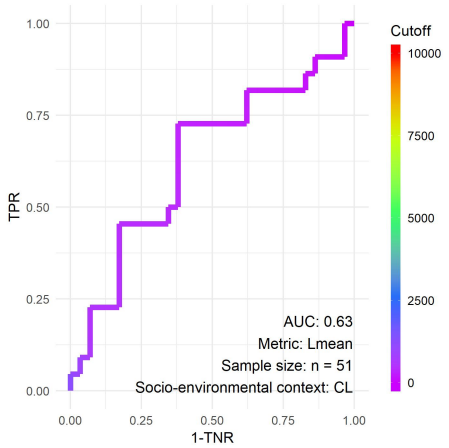
(b) Belgian socio-environmental context



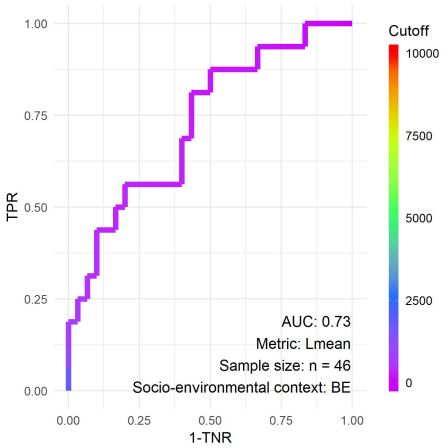
(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

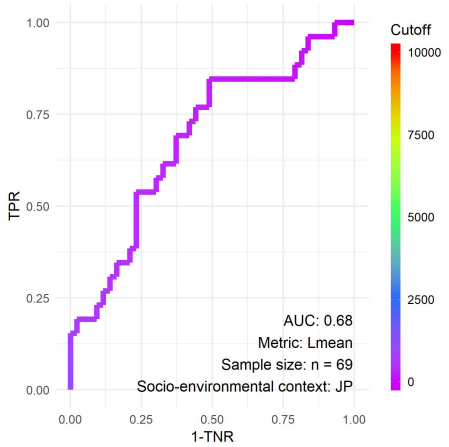
Figure G.14: ROC curves from the analyses of the performance of the E_v to predict the binary glare report in the four socio-environmental groups



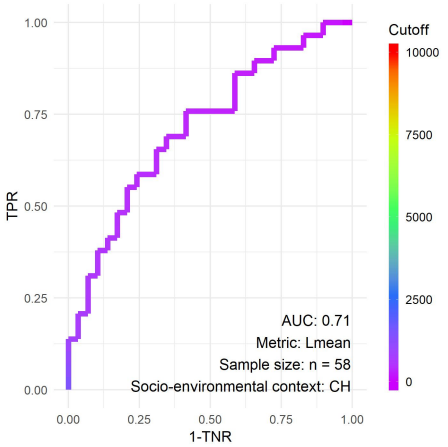
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context



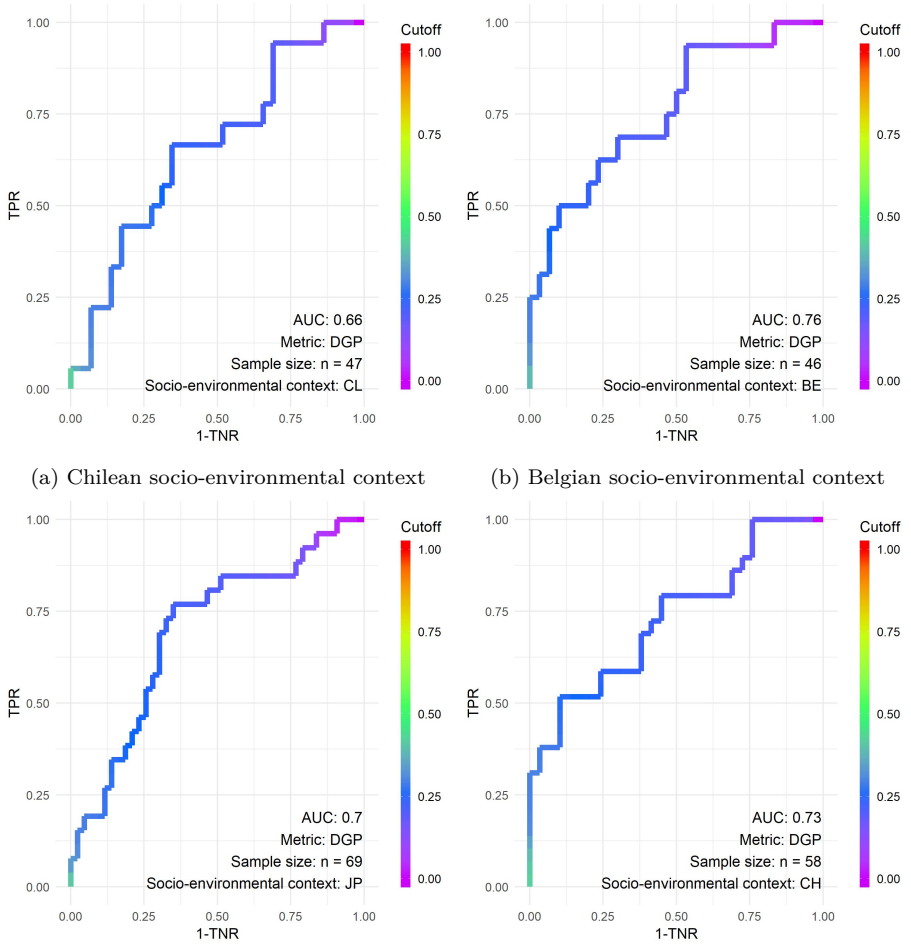
(c) Japanese socio-environmental context



(d) Swiss socio-environmental context

Figure G.15: ROC curves from the analyses of the performance of the L_{mean} to predict the binary glare report in the four socio-environmental groups

G.3 Graphs from Subsection 6.5.1 in Chapter 6



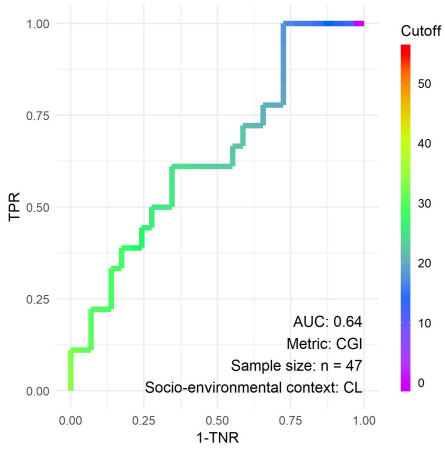
(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

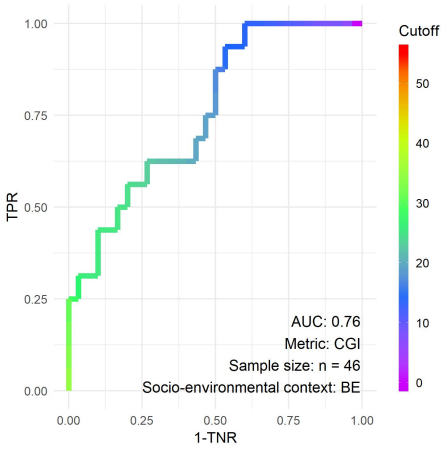
(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

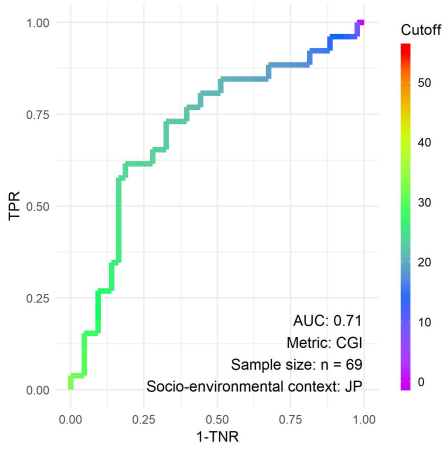
Figure G.16: ROC curves from the analyses of the performance of the DGP to predict the binary glare report in the four socio-environmental groups when the ambiguous Chilean data points are discarded



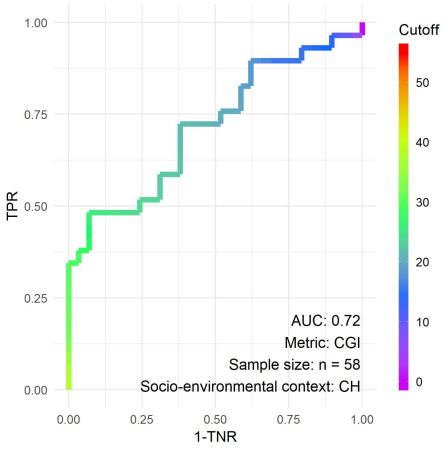
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context

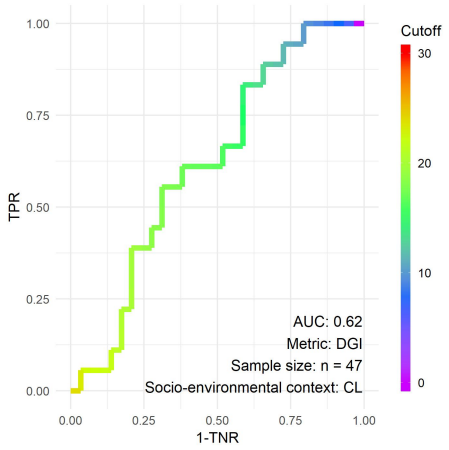


(c) Japanese socio-environmental context

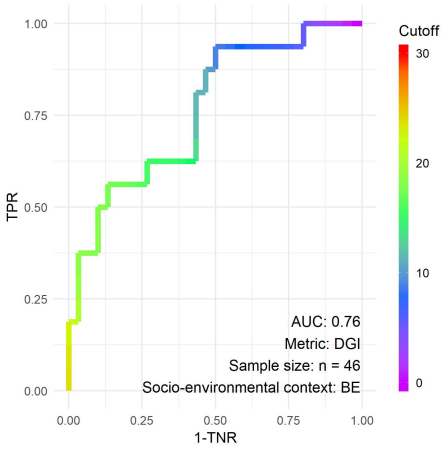


(d) Swiss socio-environmental context

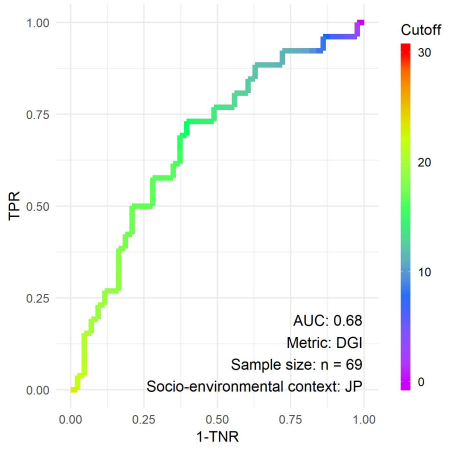
Figure G.17: ROC curves from the analyses of the performance of the CGI to predict the binary glare report in the four socio-environmental groups when the ambiguous Chilean data points are discarded



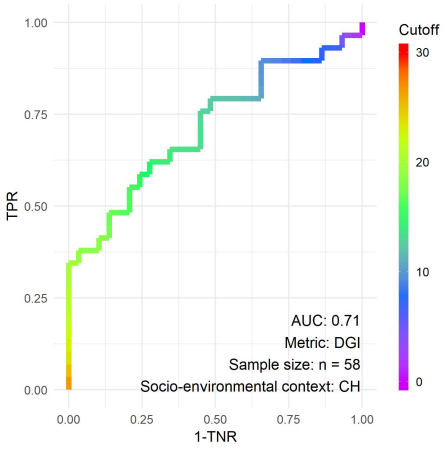
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context

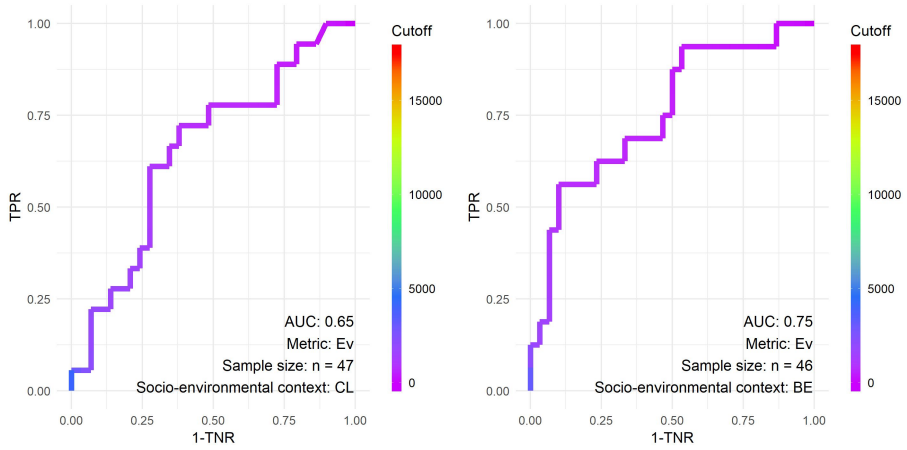


(c) Japanese socio-environmental context



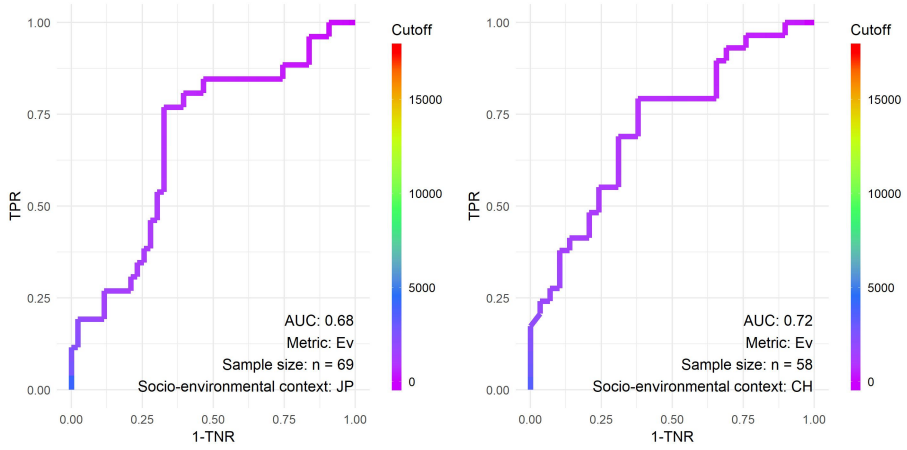
(d) Swiss socio-environmental context

Figure G.18: ROC curves from the analyses of the performance of the DGI to predict the binary glare report in the four socio-environmental groups when the ambiguous Chilean data points are discarded



(a) Chilean socio-environmental context

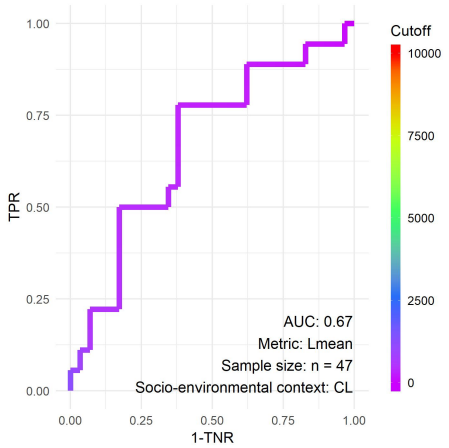
(b) Belgian socio-environmental context



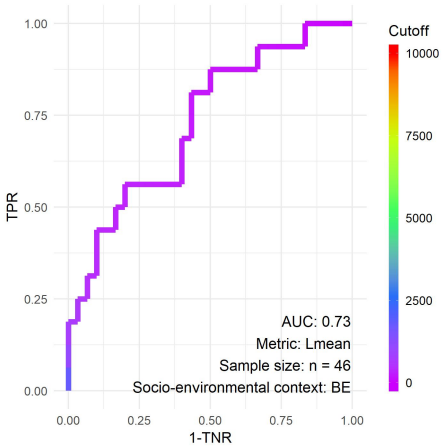
(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

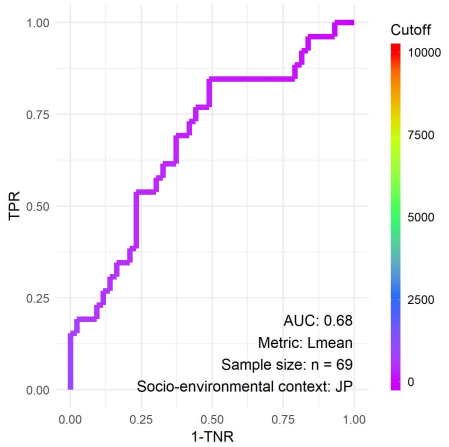
Figure G.19: ROC curves from the analyses of the performance of the E_v to predict the binary glare report in the four socio-environmental groups when the ambiguous Chilean data points are discarded



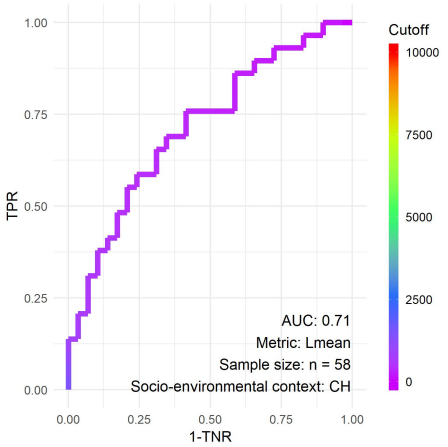
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context



(c) Japanese socio-environmental context



(d) Swiss socio-environmental context

Figure G.20: ROC curves from the analyses of the performance of the L_{mean} to predict the binary glare report in the four socio-environmental groups when the ambiguous Chilean data points are discarded

G.4 Graphs from Subsection 6.6.1 in Chapter 6

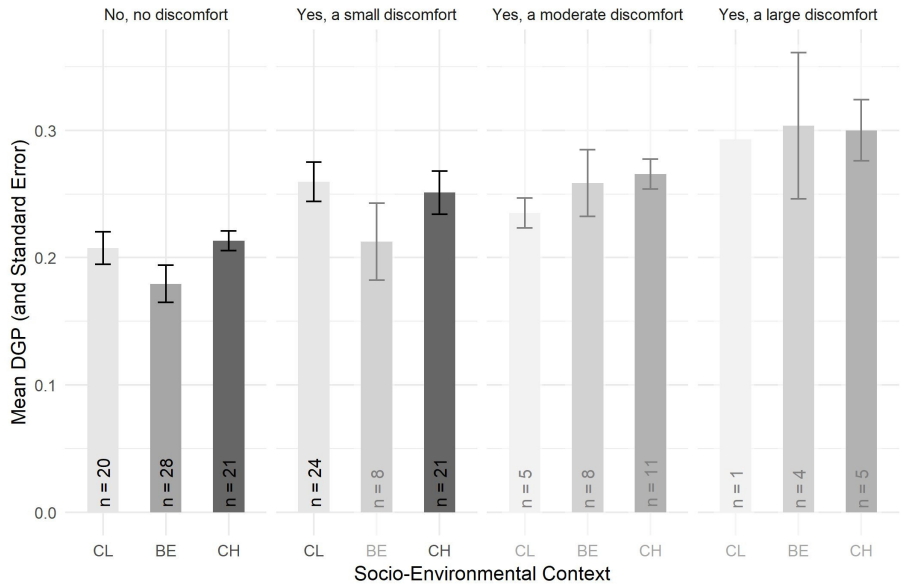


Figure G.21: Bar plots of the mean DGP values for each category of the 4-point glare rating scale A for three socio-environmental groups; the bars based on less than 15 data points have been faded as the mean value of these bars should be considered carefully

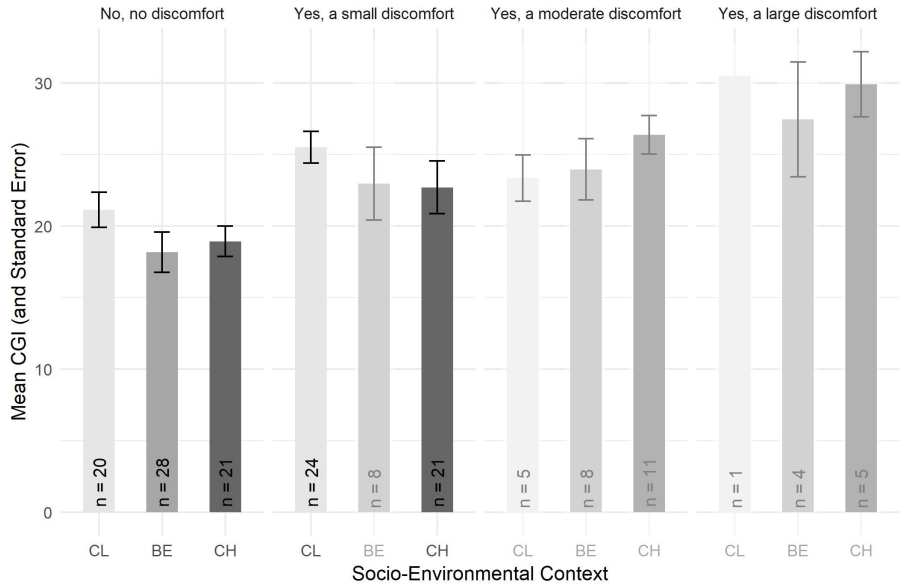


Figure G.22: Bar plots of the mean CGI values for each category of the 4-point glare rating scale A for three socio-environmental groups; the bars based on less than 15 data points have been faded as the mean value of these bars should be considered carefully

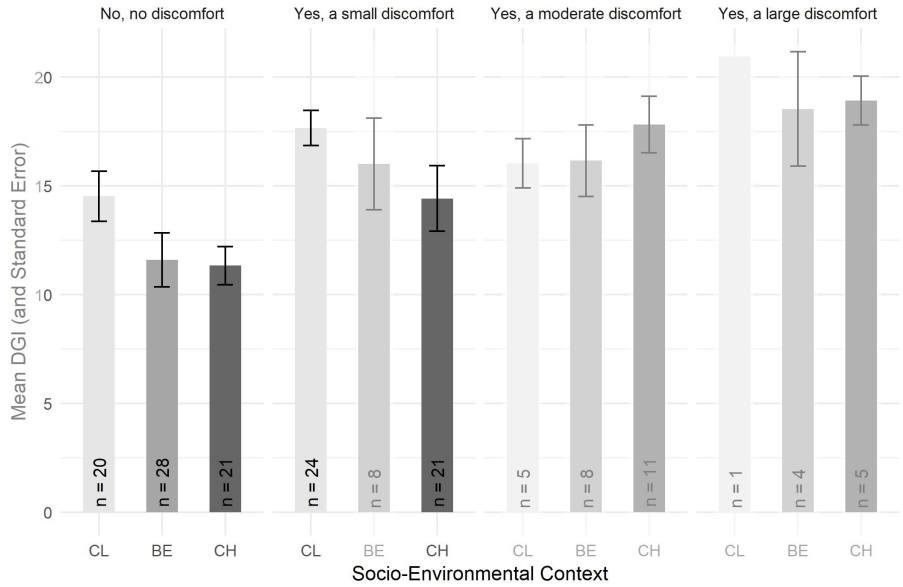


Figure G.23: Bar plots of the mean DGI values for each category of the 4-point glare rating scale A for three socio-environmental groups; the bars based on less than 15 data points have been faded as the mean value of these bars should be considered carefully

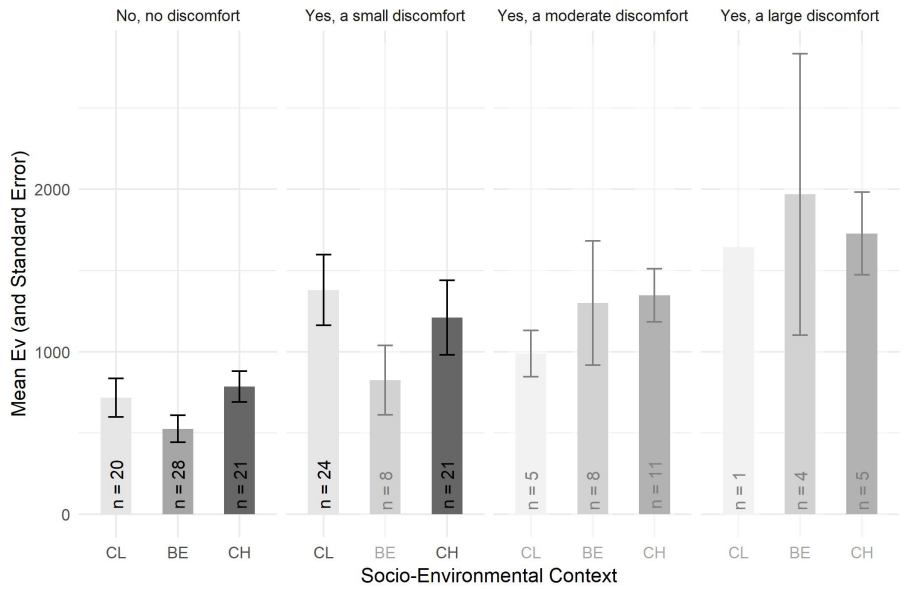


Figure G.24: Bar plots of the mean E_v values for each category of the 4-point glare rating scale A for three socio-environmental groups; the bars based on less than 15 data points have been faded as the mean value of these bars should be considered carefully

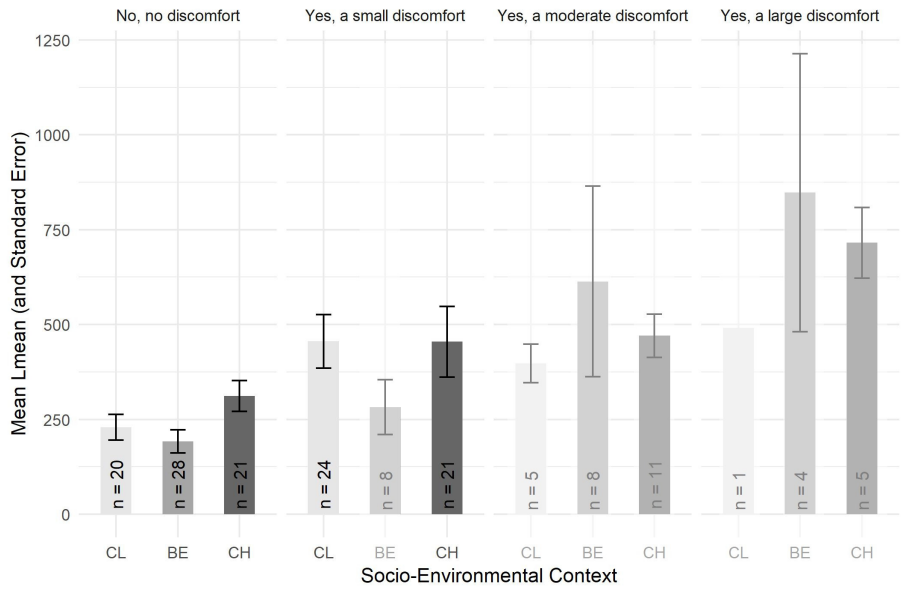


Figure G.25: Bar plots of the mean L_{mean} values for each category of the 4-point glare rating scale A for three socio-environmental groups; the bars based on less than 15 data points have been faded as the mean value of these bars should be considered carefully

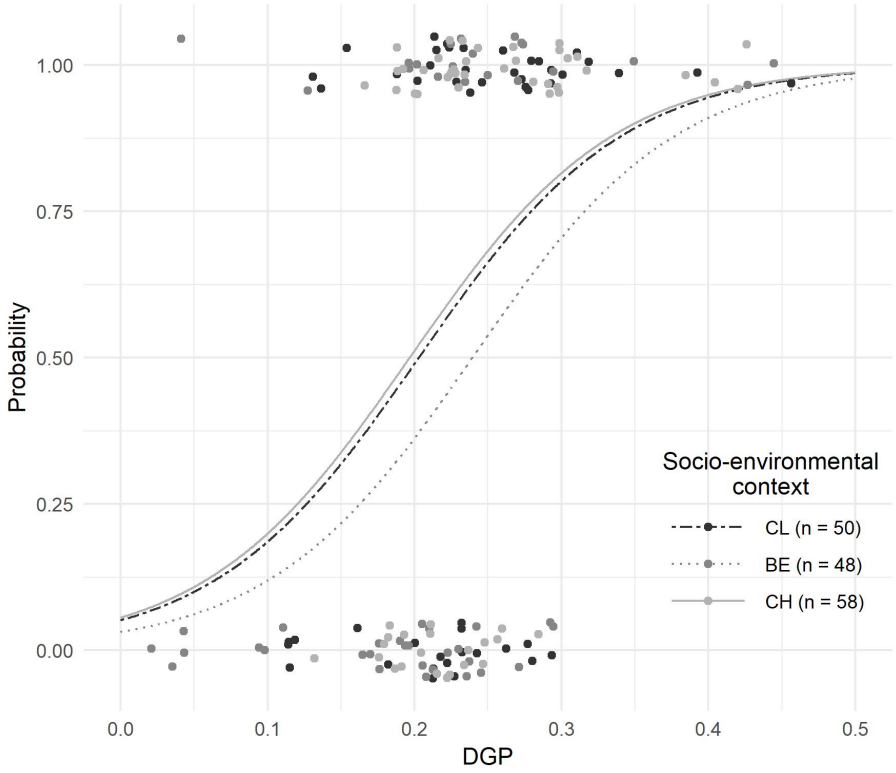


Figure G.26: Logistic growth curve of the multiple logistic regression model based on the DGP and the socio-environmental context to predict the binary transformation of the ratings made on the 4-point glare rating scale A

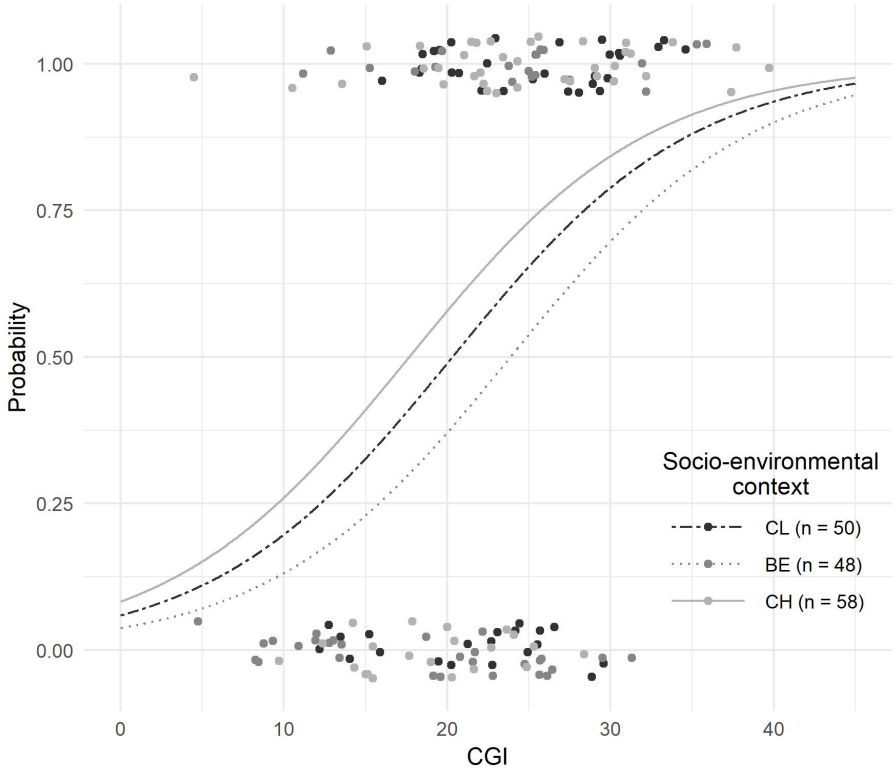


Figure G.27: Logistic growth curve of the multiple logistic regression model based on the CGI and the socio-environmental context to predict the binary transformation of the ratings made on the 4-point glare rating scale A

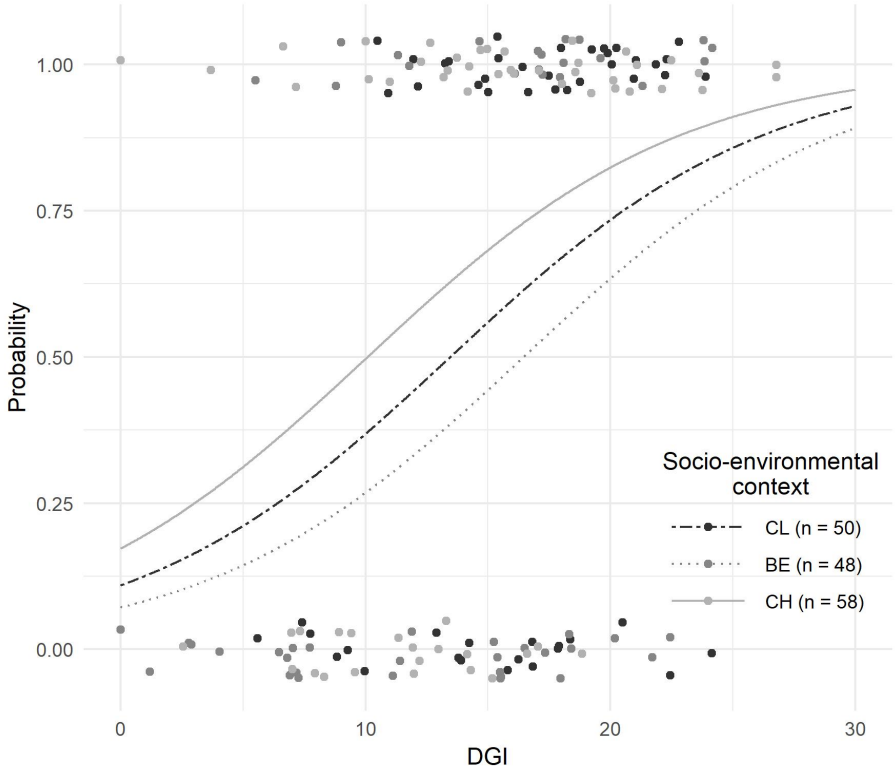


Figure G.28: Logistic growth curve of the multiple logistic regression model based on the DGI and the socio-environmental context to predict the binary transformation of the ratings made on the 4-point glare rating scale A

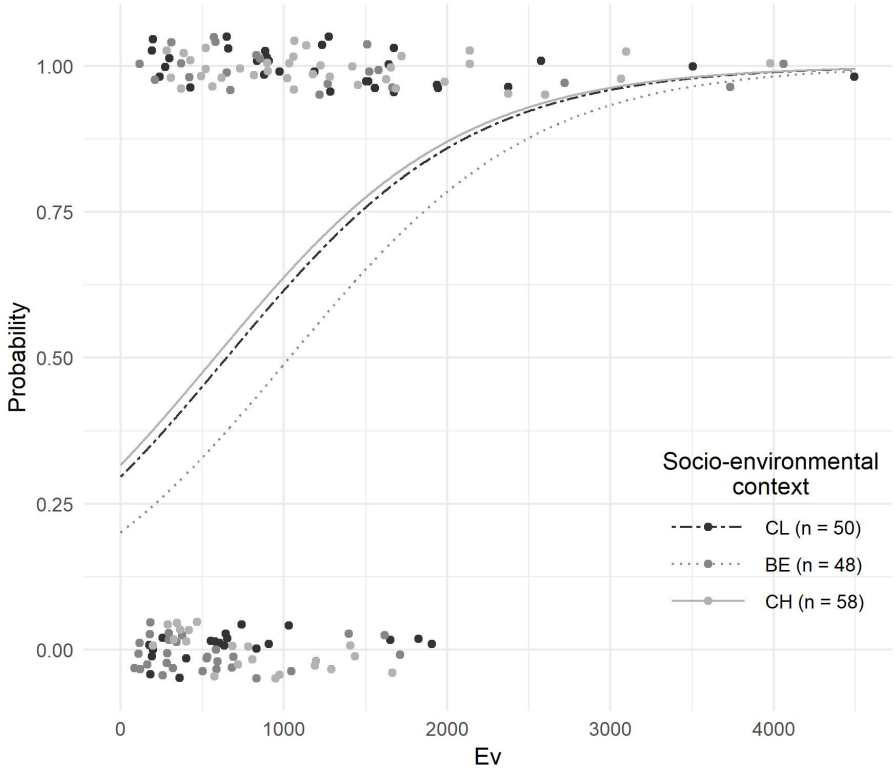


Figure G.29: Logistic growth curve of the multiple logistic regression model based on the E_v and the socio-environmental context to predict the binary transformation of the ratings made on the 4-point glare rating scale A

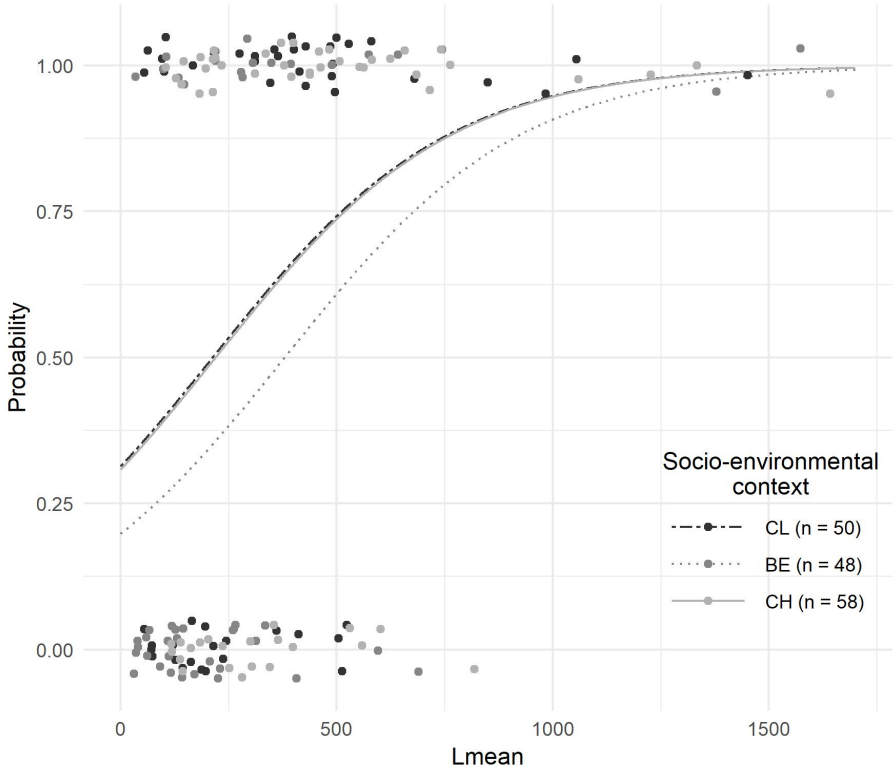


Figure G.30: Logistic growth curve of the multiple logistic regression model based on the L_{mean} and the socio-environmental context to predict the binary transformation of the ratings made on the 4-point glare rating scale A

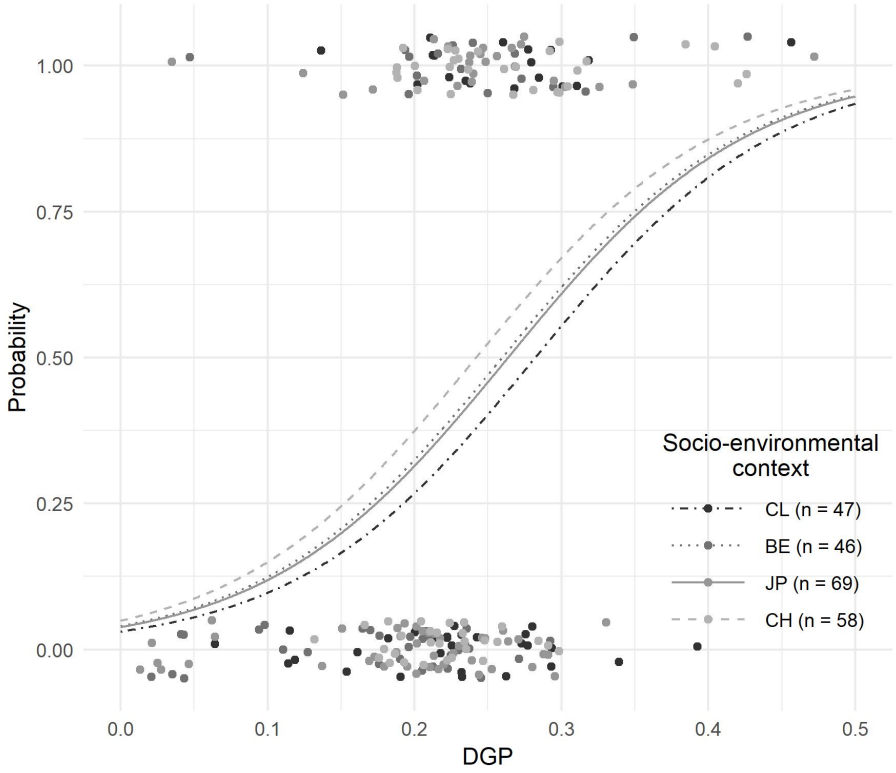


Figure G.31: Logistic growth curve of the multiple logistic regression model based on the DGP and the socio-environmental context to predict the binary glare report

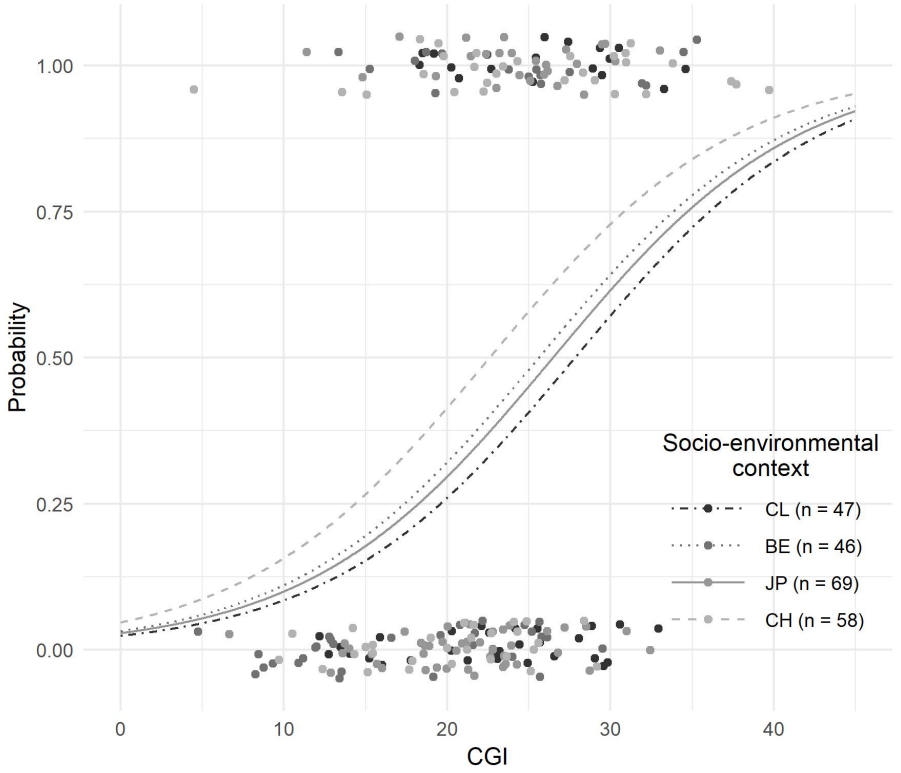


Figure G.32: Logistic growth curve of the multiple logistic regression model based on the CGI and the socio-environmental context to predict the binary glare report

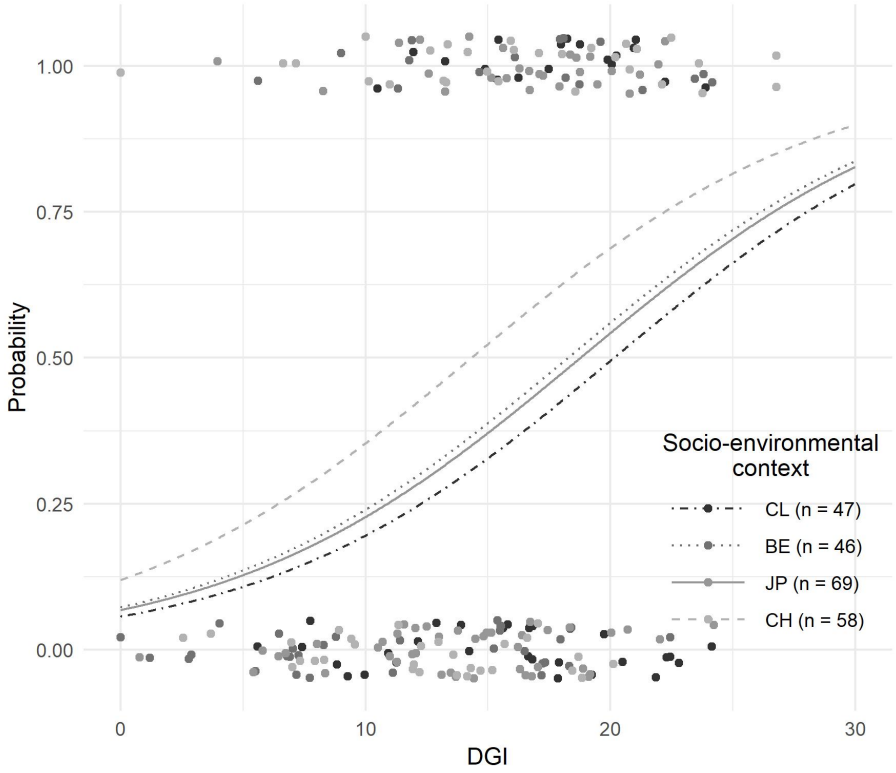


Figure G.33: Logistic growth curve of the multiple logistic regression model based on the DGI and the socio-environmental context to predict the binary glare report

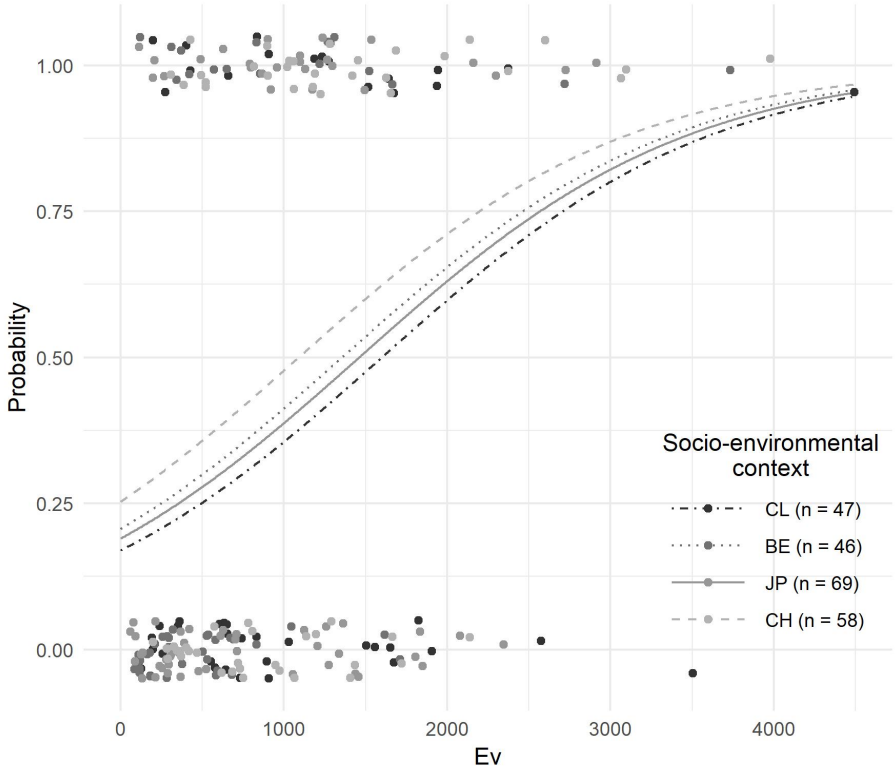


Figure G.34: Logistic growth curve of the multiple logistic regression model based on the E_v and the socio-environmental context to predict the binary glare report

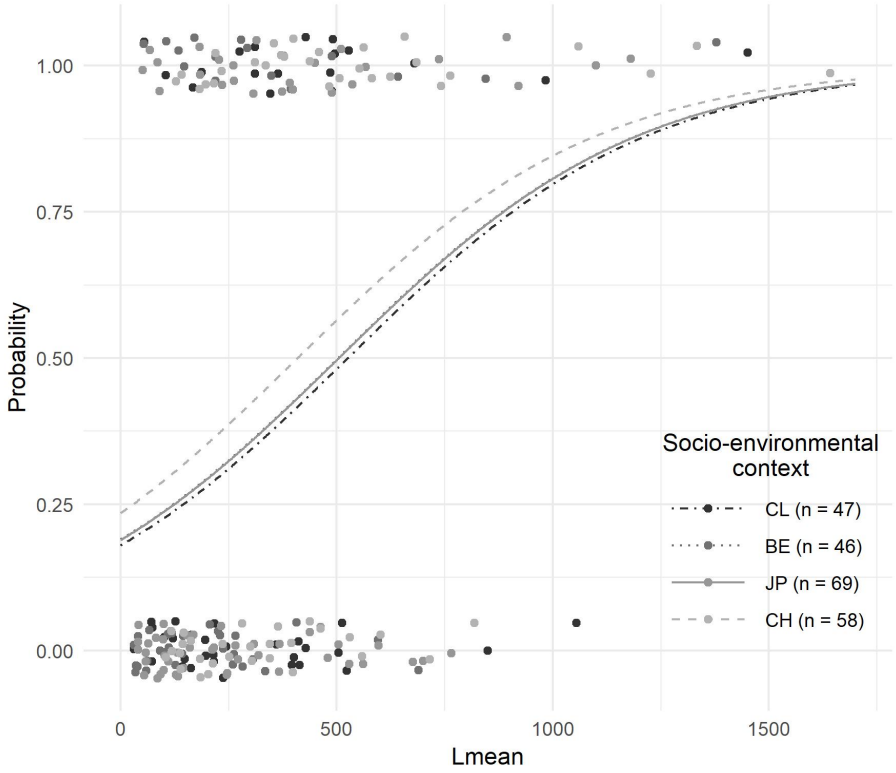


Figure G.35: Logistic growth curve of the multiple logistic regression model based on the L_{mean} and the socio-environmental context to predict the binary glare report

G.5 Graphs from Subsection 7.3.1 in Chapter 7

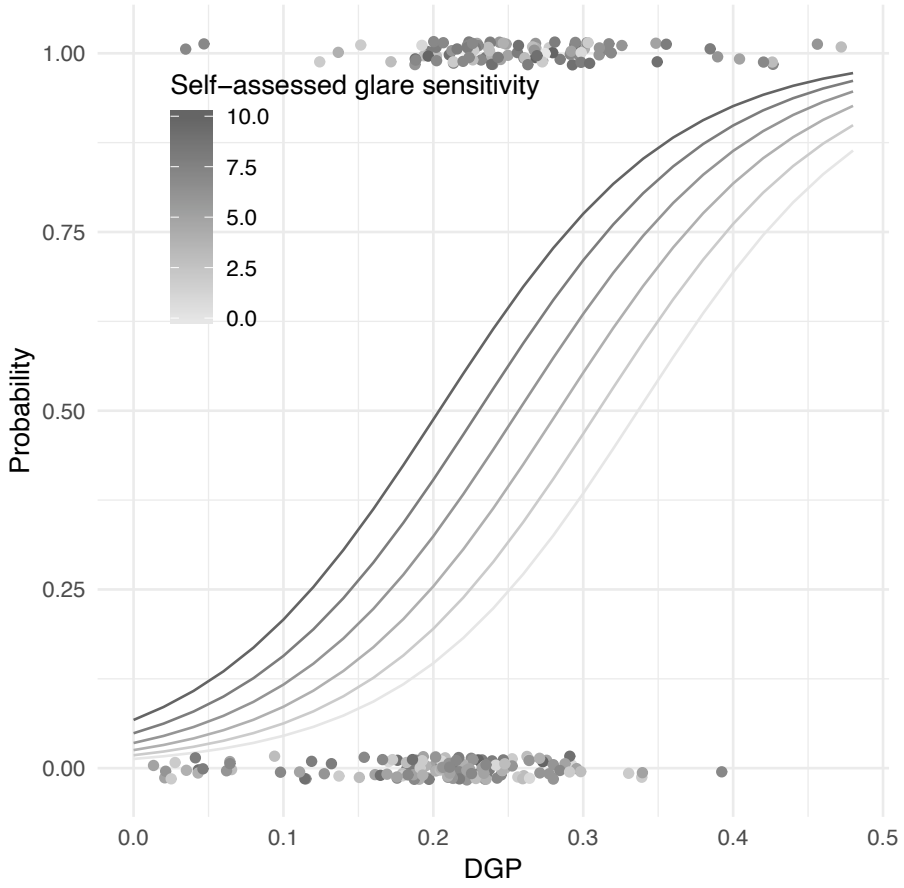


Figure G.36: Logistic growth curve of the multiple logistic regression model based on the DGP and the self-assessed glare sensitivity of the subject to predict the binary glare report

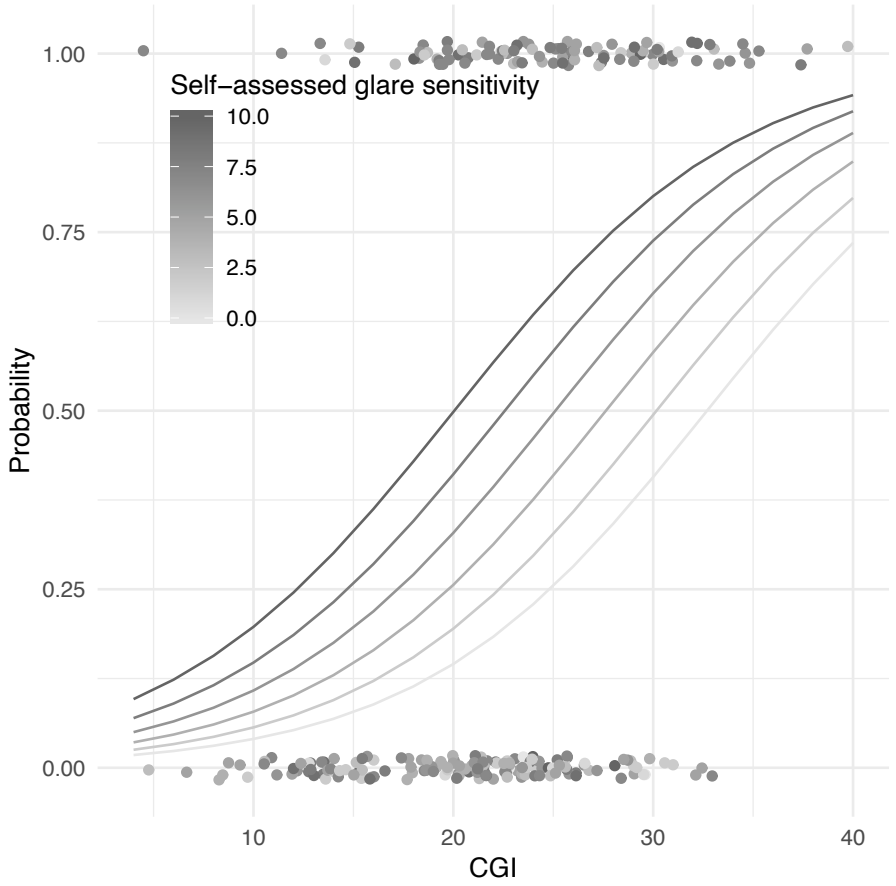


Figure G.37: Logistic growth curve of the multiple logistic regression model based on the CGI and the self-assessed glare sensitivity of the subject to predict the binary glare report

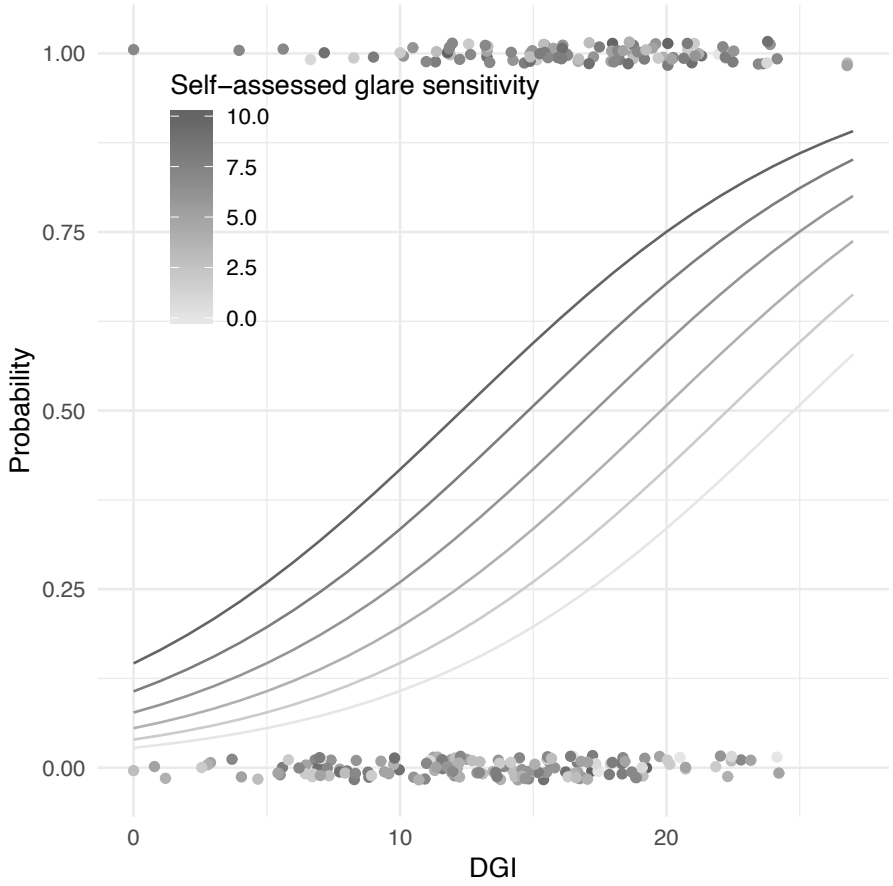


Figure G.38: Logistic growth curve of the multiple logistic regression model based on the DGI and the self-assessed glare sensitivity of the subject to predict the binary glare report

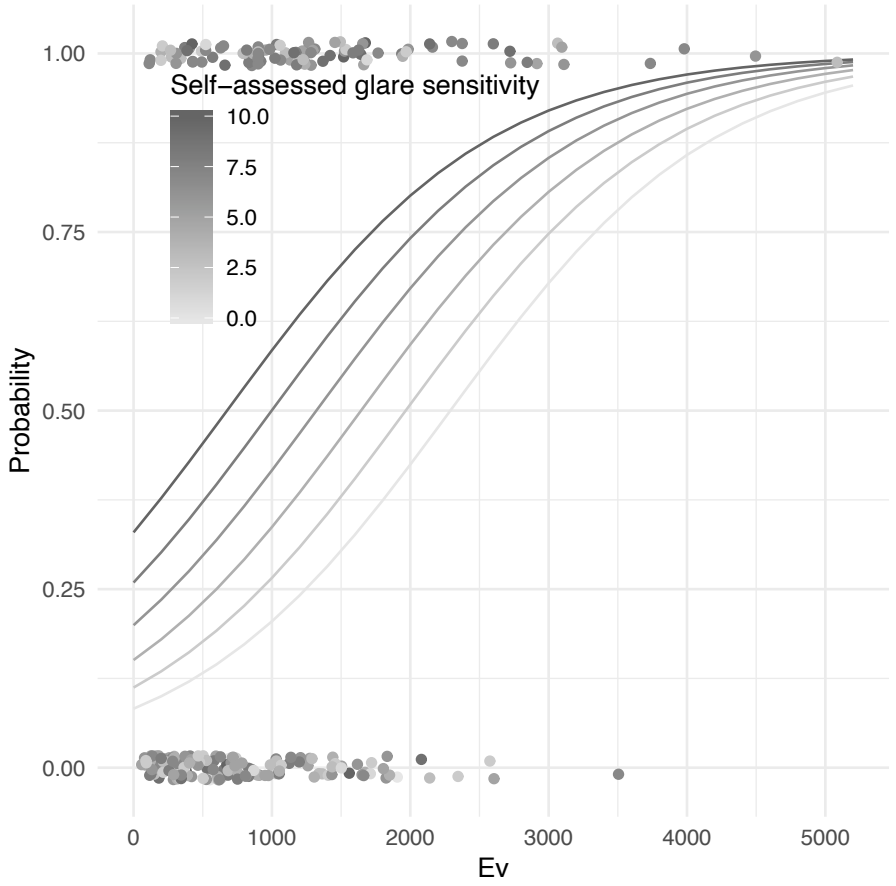


Figure G.39: Logistic growth curve of the multiple logistic regression model based on the E_v and the self-assessed glare sensitivity of the subject to predict the binary glare report

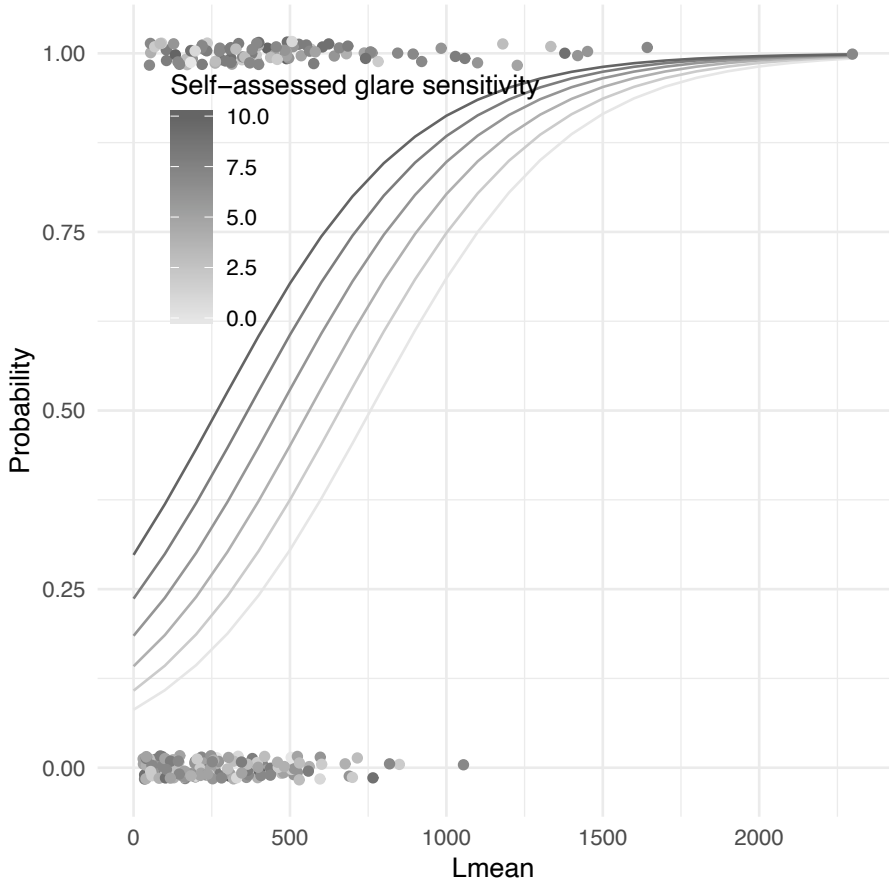


Figure G.40: Logistic growth curve of the multiple logistic regression model based on the L_{mean} and the self-assessed glare sensitivity of the subject to predict the binary glare report

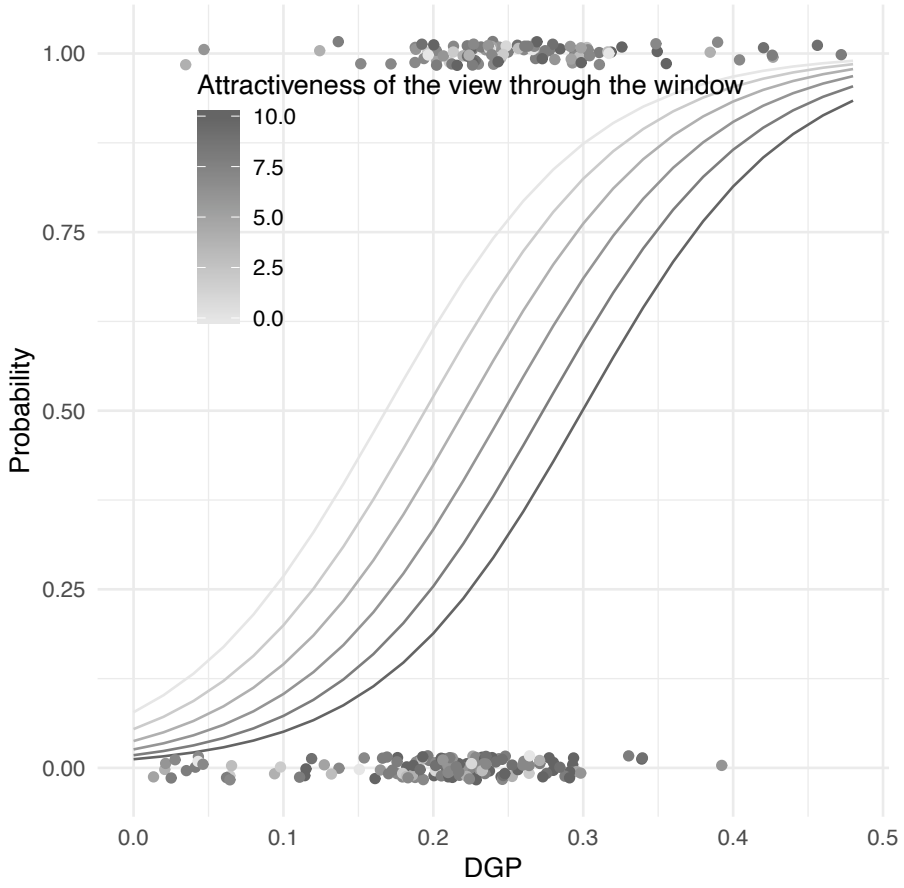


Figure G.41: Logistic growth curve of the multiple logistic regression model based on the DGP and the attractiveness of the view through the window to predict the binary glare report

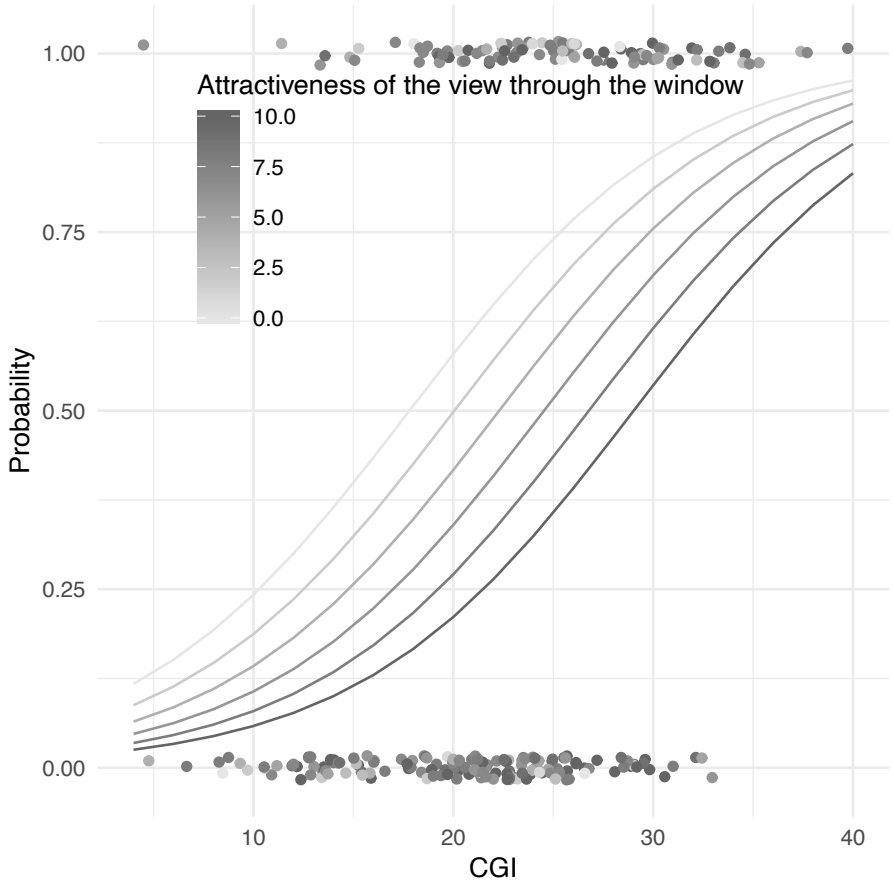


Figure G.42: Logistic growth curve of the multiple logistic regression model based on the CGI and the attractiveness of the view through the window to predict the binary glare report

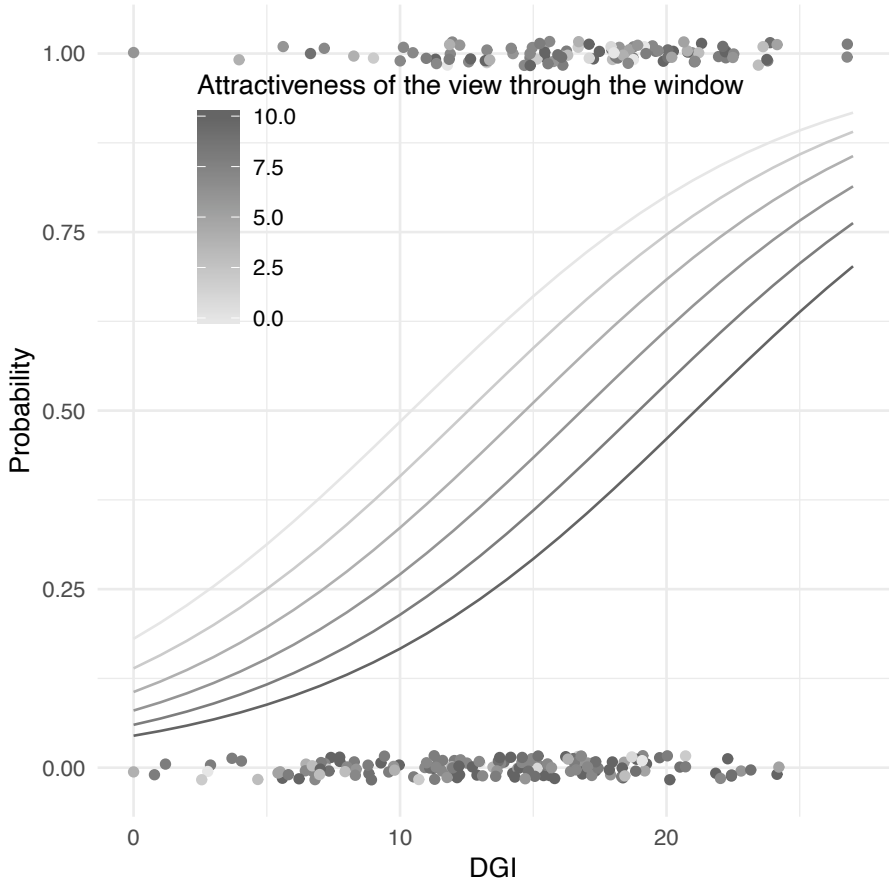


Figure G.43: Logistic growth curve of the multiple logistic regression model based on the DGI and the attractiveness of the view through the window to predict the binary glare report

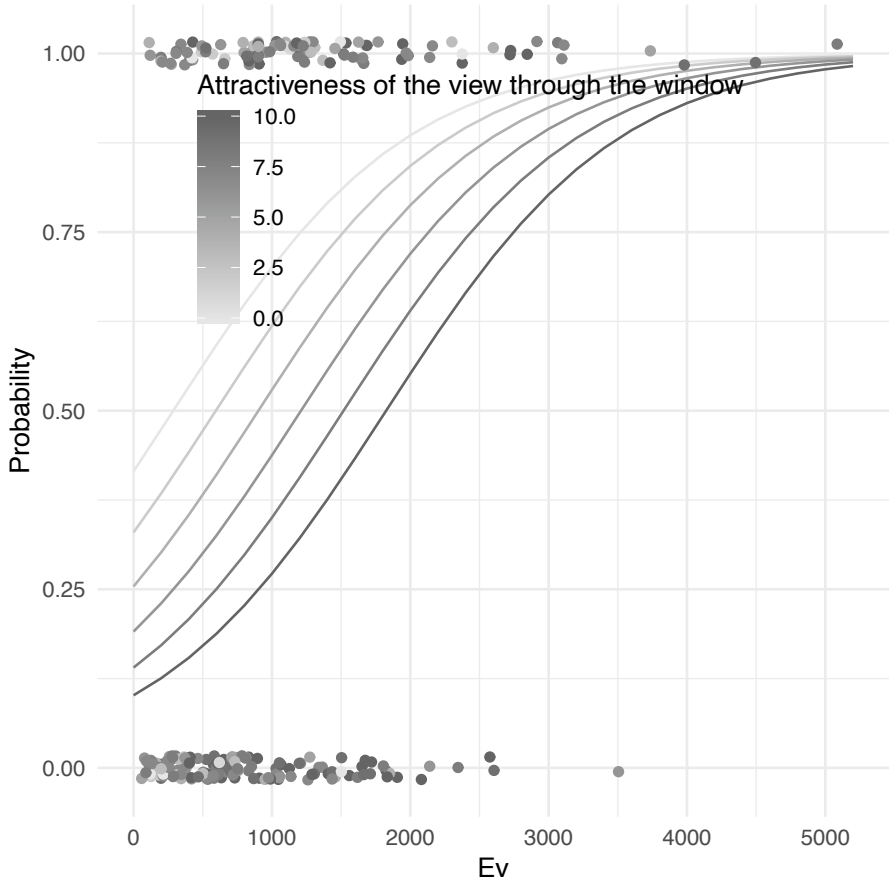


Figure G.44: Logistic growth curve of the multiple logistic regression model based on the E_v and the attractiveness of the view through the window to predict the binary glare report

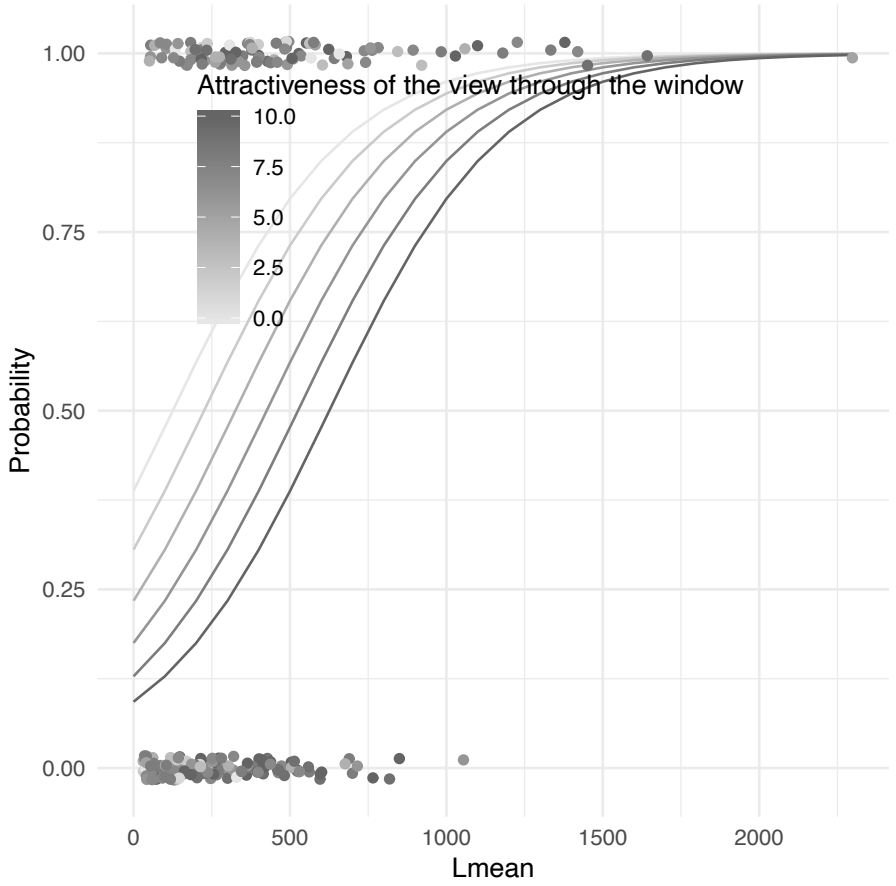
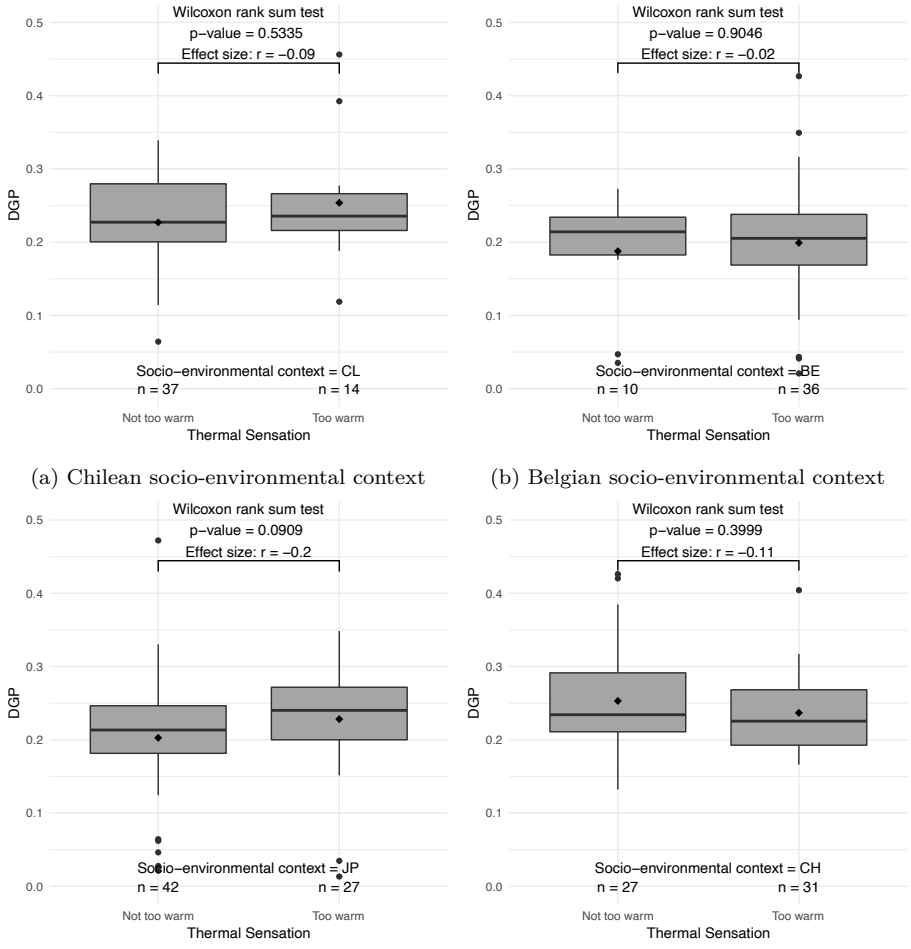


Figure G.45: Logistic growth curve of the multiple logistic regression model based on the L_{mean} and the attractiveness of the view through the window to predict the binary glare report

G.6 Graphs from Subsection 7.4.1 in Chapter 7



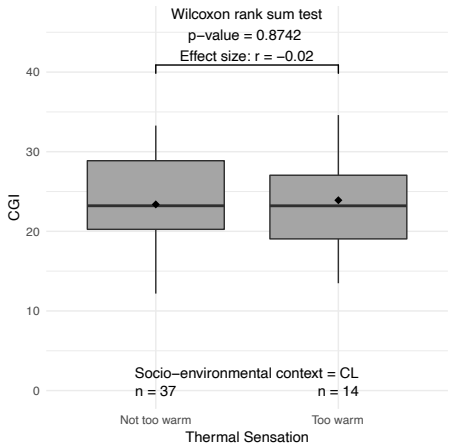
(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

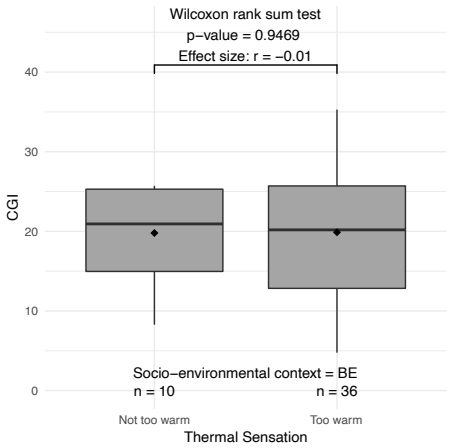
(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

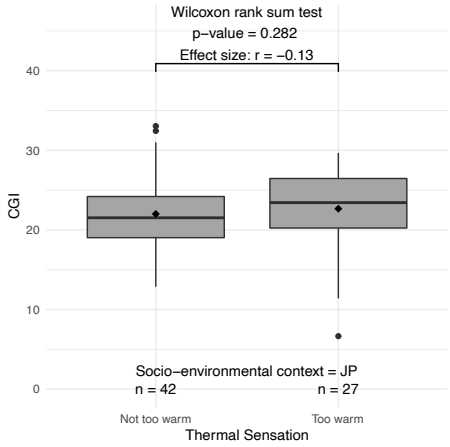
Figure G.46: Results of the Wilcoxon rank sum test for the influence of the DGP on thermal sensation, and box plots representing the distribution of the data for DGP per categories in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers



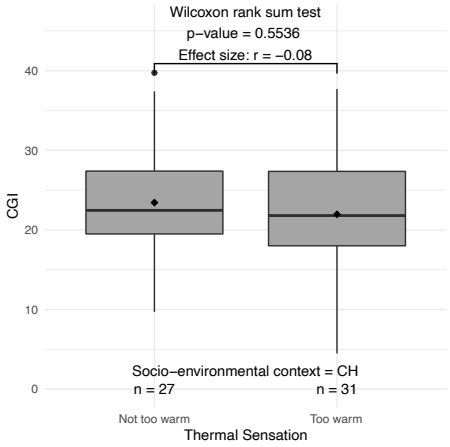
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context

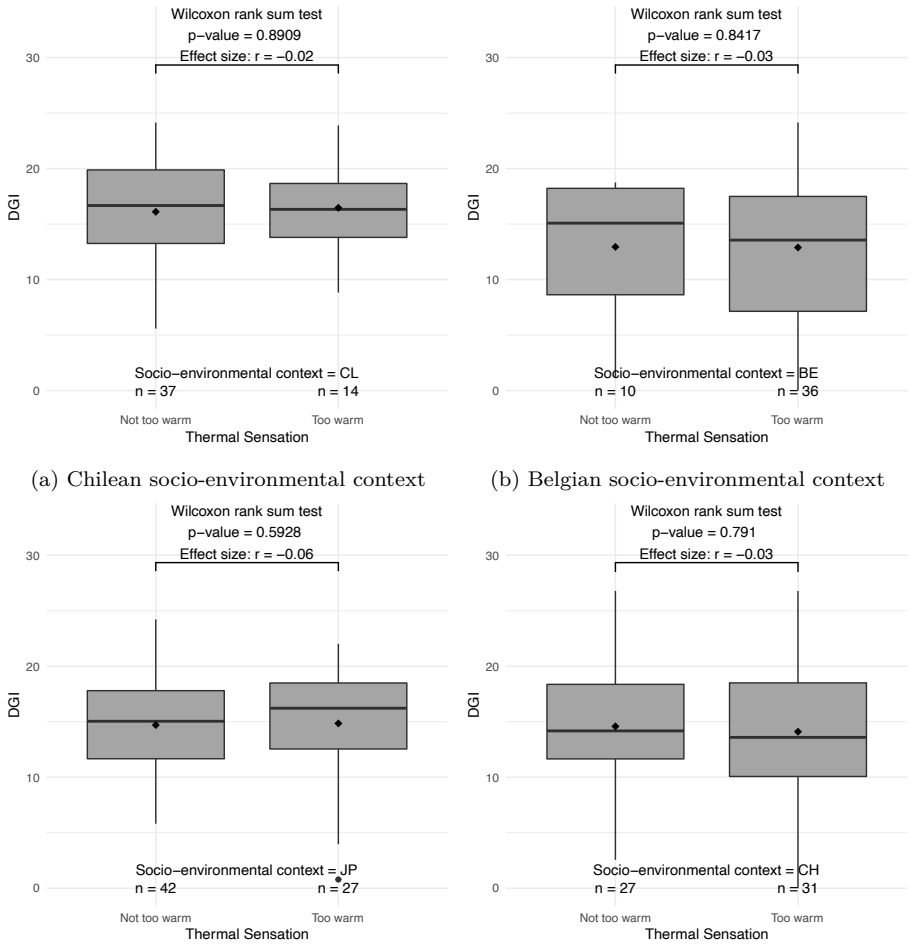


(c) Japanese socio-environmental context



(d) Swiss socio-environmental context

Figure G.47: Results of the Wilcoxon rank sum test for the influence of the CGI on thermal sensation, and box plots representing the distribution of the data for CGI per categories in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers



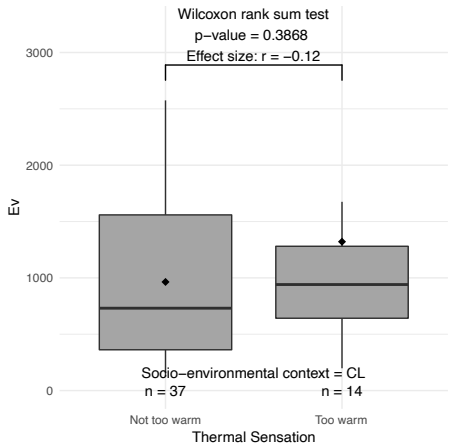
(a) Chilean socio-environmental context

(b) Belgian socio-environmental context

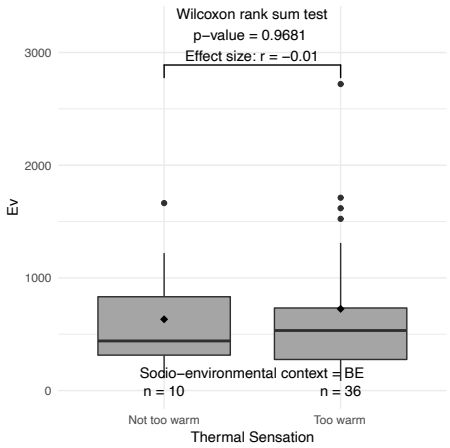
(c) Japanese socio-environmental context

(d) Swiss socio-environmental context

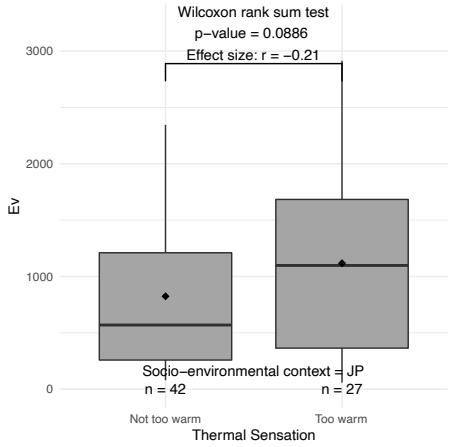
Figure G.48: Results of the Wilcoxon rank sum test for the influence of the DGI on thermal sensation, and box plots representing the distribution of the data for DGI per categories in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers



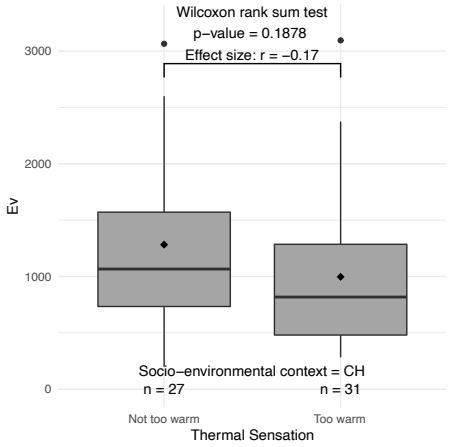
(a) Chilean socio-environmental context



(b) Belgian socio-environmental context

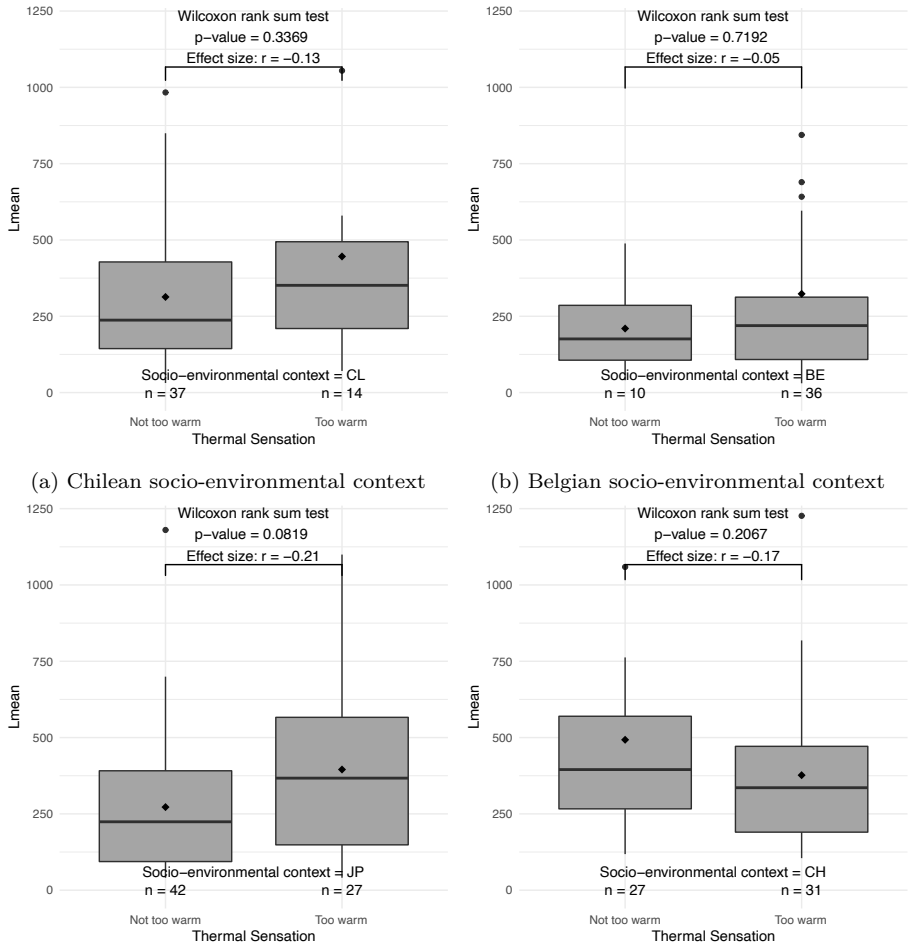


(c) Japanese socio-environmental context



(d) Swiss socio-environmental context

Figure G.49: Results of the Wilcoxon rank sum test for the influence of the E_v on thermal sensation, and box plots representing the distribution of the data for E_v per categories in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers



(a) Chilean socio-environmental context

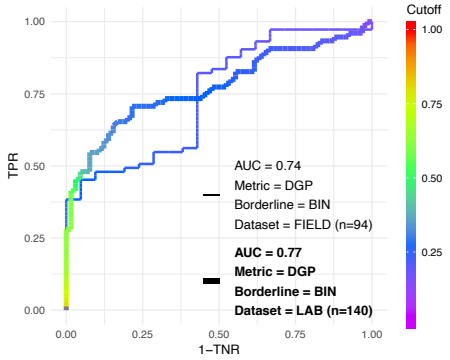
(b) Belgian socio-environmental context

(c) Japanese socio-environmental context

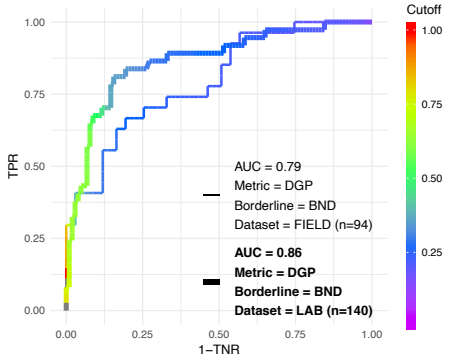
(d) Swiss socio-environmental context

Figure G.50: Results of the Wilcoxon rank sum test for the influence of the L_{mean} on thermal sensation, and box plots representing the distribution of the data for L_{mean} per categories in the four socio-environmental groups; the diamond dot corresponds to the mean, the band inside the box to the median, and the round dots to the outliers

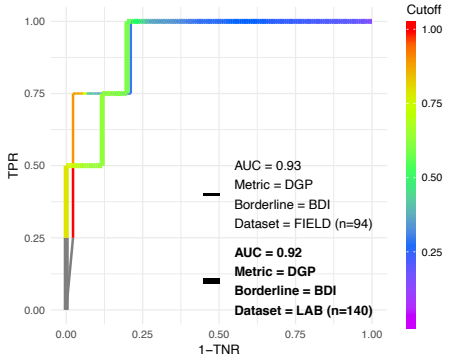
G.7 Graphs from Subsection 8.3.1 in Chapter 8



(a) ROC curve for BIN

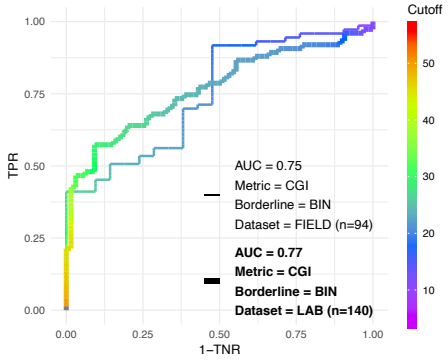


(b) ROC curve for BND

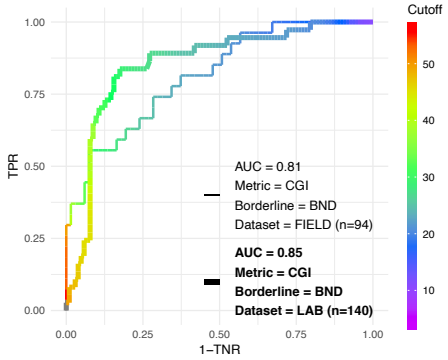


(c) ROC curve for BDI

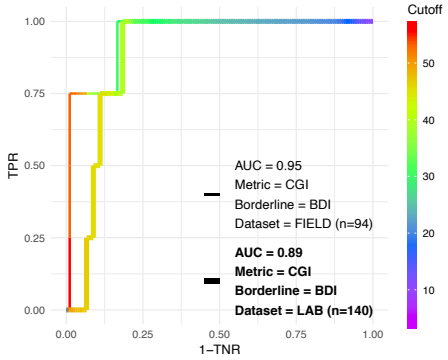
Figure G.51: ROC curves from the analyses of the performance of the DGP to predict the first (BIN), second (BND), and third (BDI) binary transformations of the ratings on the 4-point glare rating scale C for the field study and the laboratory study groups



(a) ROC curve for BIN

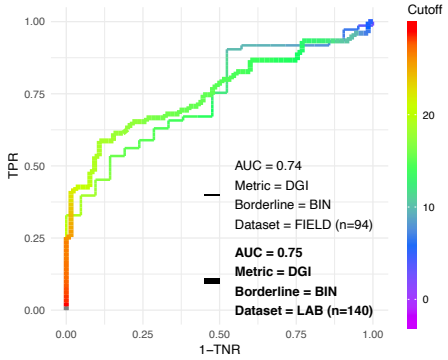


(b) ROC curve for BND

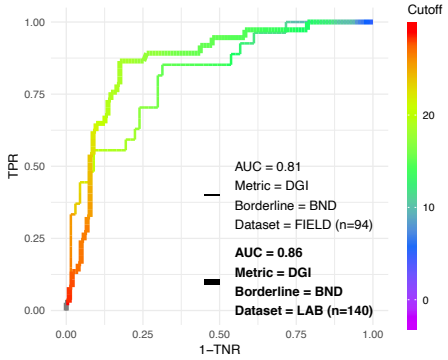


(c) ROC curve for BDI

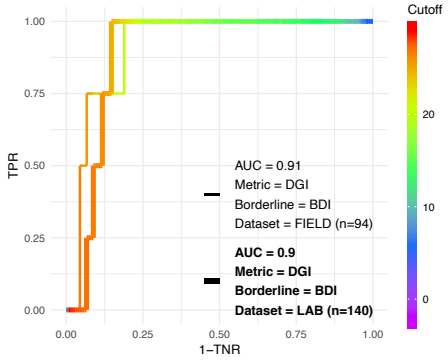
Figure G.52: ROC curves from the analyses of the performance of the CGI to predict the first (BIN), second (BND), and third (BDI) binary transformations of the ratings on the 4-point glare rating scale C for the field study and the laboratory study groups



(a) ROC curve for BIN

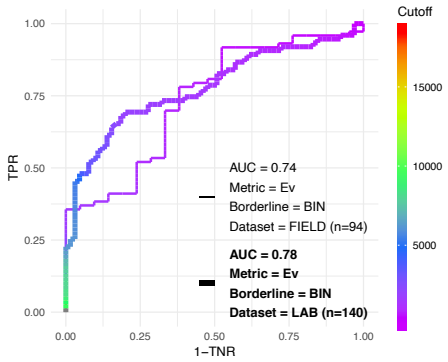


(b) ROC curve for BND

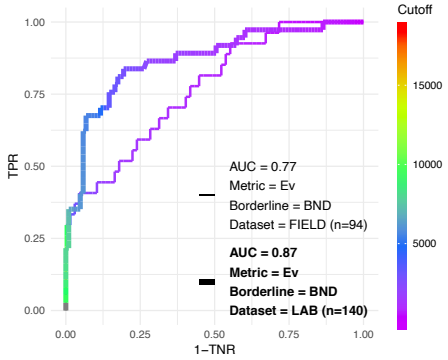


(c) ROC curve for BDI

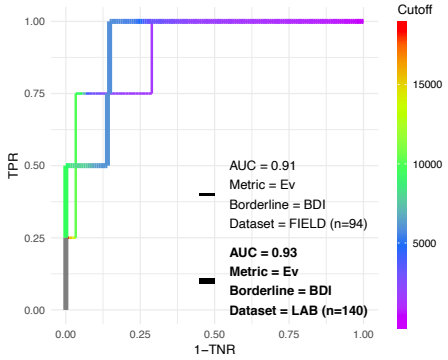
Figure G.53: ROC curves from the analyses of the performance of the DGI to predict the first (BIN), second (BND), and third (BDI) binary transformations of the ratings on the 4-point glare rating scale C for the field study and the laboratory study groups



(a) ROC curve for BIN

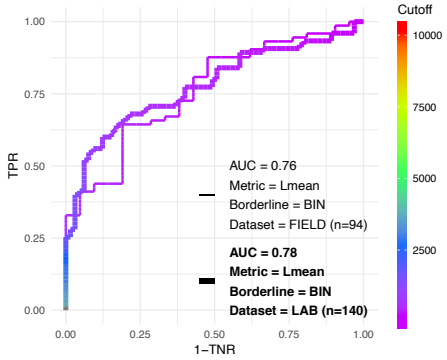


(b) ROC curve for BND

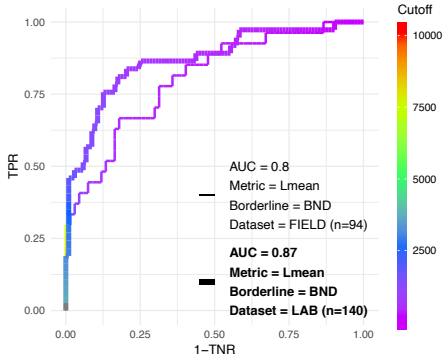


(c) ROC curve for BDI

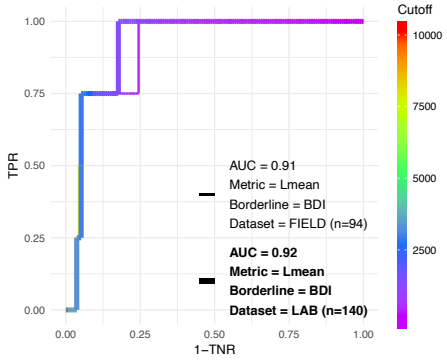
Figure G.54: ROC curves from the analyses of the performance of the E_v to predict the first (BIN), second (BND), and third (BDI) binary transformations of the ratings on the 4-point glare rating scale C for the field study and the laboratory study groups



(a) ROC curve for BIN



(b) ROC curve for BND



(c) ROC curve for BDI

Figure G.55: ROC curves from the analyses of the performance of the L_{mean} to predict the first (BIN), second (BND), and third (BDI) binary transformations of the ratings on the 4-point glare rating scale C for the field study and the laboratory study groups

Appendix H

Journal Article in Leukos

The appended article is the accepted manuscript of the review article published in LEUKOS [Pierson et al. 2018b], reproduced with permission of the Illuminating Engineering Society.

Review of factors influencing discomfort glare perception from daylight

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[2] Laboratory of Integrated Performance in Design, Ecole polytechnique fédérale de Lausanne, Lausanne, Switzerland

Abstract - As well-being is becoming a major challenge in construction nowadays alongside energy efficiency, there is an increasing need to be able to quantify discomfort in buildings. In the case of discomfort glare, the kind of glare provoking an irritating or distracting effect, no current indices can properly explain the high variability existing between individuals' discomfort glare perceptions. This is due to the fact that some of the factors influencing discomfort glare perception are still unknown and the mechanism behind the discomfort glare process is not well understood. Therefore, this paper aims to review the factors potentially influencing discomfort glare perception from daylight. Every factor having been studied at least once for its potential influence on discomfort glare perception has been listed, described and analyzed. Furthermore, this study categorizes the influence of these factors on discomfort glare by introducing an influence indicator based on the number of studies having investigated the factor, the sample size of these studies, and the agreement between them. The suggested categories rate a factor influence as "almost certain", "more likely", "somewhat likely", "inconclusive", "somewhat unlikely", "less likely", or "almost certainly null". Tables summarize the main information about the studies and the influencing factors. As expected, factors almost certainly influencing discomfort glare perception are the luminance of the glare source, the adaptation level, the contrast effect, the size and position of the glare source. On the opposite, factors which almost certainly do not influence discomfort glare perception are the gender and the optical correction of the observer. All other factors from the list of thirty, such as the attractiveness of the view through the window or the culture of the observer, require additional studies to determine whether or not they are influencing discomfort glare perception.

Keywords - discomfort glare, daylighting, visual perception, glare metrics, influencing factors

1. Introduction

Nowadays, energy efficiency and well-being are both major challenges in construction. With the rapid development of new technologies, systems are implemented in buildings to control interactions and operations of special techniques such as heating, ventilation or air conditioning. This is also the case for lighting. In a growing number of office buildings, shading devices and artificial lighting are integrated in systems working on the basis of models and sensors. The control algorithms implemented in these systems aim to use indices such as the Daylight Glare Probability (DGP) or the Discomfort Glare Index (DGI) to evaluate visual discomfort. Thresholds of visual discomfort are therefore predetermined in the models and if the values evaluated by the indices are not consistent with these thresholds, actions are taken by the system (Chaiwiwatworakul et al. 2009, Chan and Tzempelikos 2013, Goovaerts et al. 2017, Shen et al. 2014). But the visual discomfort indices used in those systems have not been developed to provide such accurate threshold values. This is especially true for indices predicting discomfort glare, which is the kind of glare provoking an irritating or distracting effect but not impairing the view (CIE 1983). As the mechanisms governing discomfort glare are still unknown, current indices predict the degree of perceived discomfort glare by approximating a value, but certainly not by defining a precise threshold. Approximating the degree of perceived discomfort glare has been the best way so far to take this effect into consideration in the occupant's well-being evaluation.

There exists a high variability between individuals' discomfort glare perception, as it has already been pointed out several times (Boyce 2014, Eble-Hankins and Waters 2005, Galasiu and Veitch 2006,

Rodriguez and Pattini 2014, Stone and Harker 1973, Van Den Wymelenberg et al. 2010, Wirtschafter and Bourassa 1966). This variability could probably be better understood by reconsidering discomfort glare indices. In addition to the physical quantities currently used, other variables such as physiological or psychological factors could influence the degree of perceived discomfort glare and explain this large variability between individuals. One of the current knowledge gaps in discomfort glare is the lack of information about the moderating effect of culture, age or outside view for instance (Van Den Wymelenberg 2014).

This paper aims to go back to the foundations of discomfort glare indices by making an exhaustive review of factors potentially influencing the degree of perceived discomfort glare from windows. First, a contextualization of what is currently acknowledged on discomfort glare from daylight is given. Common variables and indices related to discomfort glare from windows are summarized as well as the method used to define the factors influencing discomfort glare perception. Every factor having at least been the object of an experiment as a potential element influencing discomfort glare perception is listed, described and analyzed. At last, the conclusion sums up the factors and put forward some suggestions for future research on discomfort glare from daylighting.

2. Assessment of daylight discomfort glare factors

In order to describe the factors playing a role in a particular process, understanding the mechanism behind this process is highly recommended. This is not conceivable for discomfort glare since there is no solid scientific explanation behind this process. Discomfort glare is defined by the Commission Internationale de l'Eclairage (CIE 1983) as "*glare which causes discomfort without necessarily impairing the vision of objects*". The indices developed to predict the degree of perceived discomfort glare are made of variables which contributions have only been proved through statistical inferences.

Four physical quantities are commonly used as variables of discomfort glare equations. These variables, related to lighting or to space, are:

- the luminance of the glare source, which is the intensity of the luminous flux emitted par unit area of the source;
- the adaptation level, which is either defined as the luminance of the background or as the vertical illuminance at eye level, namely the luminous flux reaching the eye;
- the solid angle of the glare source, which expresses the seen size of the glare source;
- the position index, which is a correction factor considering the horizontal and vertical displacements of a glare source from the line of vision of the observer.

These four variables were already mentioned by the CIE as the four physical quantities influencing discomfort glare (CIE 1983). Nowadays, most indices assessing the degree of perceived discomfort glare use them as only variables. They will be described thoroughly in Section III.

More than sixty years of research have demonstrated that discomfort glare is a sort of visual discomfort due to two main causes (Iwata et al. 2011a). Glare is defined as a "*condition of vision in which there is discomfort* (discomfort glare) *or a reduction in the ability to see details or objects* (disability glare)*, caused by an unsuitable distribution or range of luminance, or to extreme contrasts*" (CEN 2011). The two causes of discomfort glare can therefore be described as:

- the total amount of light reaching the observer's eyes is too large. This means that even if the source was seen under a proper contrast with the background, the observer would feel discomfort as his or her eyes could not adapt to the light. This first cause of discomfort glare is called the saturation or absolute glare.
- the contrast between the viewing direction (e.g. visual task) and a bright spot in the field of view is too strong. Either the observer's eyes adapt to the relatively low luminance of the visual task causing the luminance of the glare source to be too high, or the observer's eyes are forced to

adapt to a bright environment and the visual task is perceived as too dim. This discomfort glare is called the contrast or relative glare.

These two causes, namely the saturation effect and the contrast effect, should be implemented in current discomfort glare indices. The distance and the position of the glare source in the field of view should also be taken into account as discomfort glare perception will vary whether the observer is far or close to the glare source and whether the glare source is in the central or lateral part of the field of view.

Hopkinson was the first to develop an index assessing the degree of perceived discomfort glare from windows with the Cornell equation (Hopkinson 1972). The index was then modified by Chauvel et al. (Chauvel et al. 1982) to become the Daylight Glare Index (DGI):

$$DGI = 10\log_{10}\left[0.478\sum_{i=1}^{n}\frac{L_{s,i}^{1.6}*\omega_i^{0.8}}{L_b+0.07\omega^{0.5}*L_{win}*P_i^{1.6}}\right] \quad (1)$$

where $L_{s,i}$ is the luminance of the glare source(s) [cd/m²]; ω_i the solid angle of the glare source(s); L_b the luminance of the background [cd/m²]; ω the solid angle of the window; L_{win} the luminance of the window [cd/m²]; P_i the position index relative to the glare source(s).

The DGI delivers a value between 16 and 28, being considered respectively as just perceptible discomfort glare and just intolerable discomfort glare. A contradiction appears already in the formula as the authors differentiate between the luminance of the source and the luminance of the window which is supposed be the glare source in the case of daylighting. This issue will be addressed in the following section.

Iwata et al. started developing another index to assess the degree of perceived discomfort glare from windows which was first called the Glare Sensation Vote (GSV) (Iwata et al. 1992a, Iwata et al. 1992b). The GSV index was revised some years later into the Predicted Glare Sensation Vote (PGSV) (Iwata and Osterhaus 2010, Tokura et al. 1996):

when $L_s/L_b > L_{ave}/L_{ad}$ (with $L_{ave} = E_v/\pi$),

$$PGSV_{contrast} = \log\frac{L_s^{3.2}\omega^{-0.64}}{L_b^{(0.61-0.79\log\omega)}} - 8.2 \quad (2)$$

when $L_s/L_b \leq L_{ave}/L_{ad}$ (with $L_{ave} = E_v/\pi$),

$$PGSV_{saturation} = \frac{-3.87}{1+(L_{ave}/1250)^{1.7}} + 3.3 \quad (3)$$

where L_b is the background luminance [cd/m²]; L_s the luminance of the source [cd/m²]; L_{ave} the mean luminance of the visual field [cd/m²]; L_{ad} the adaptation luminance [cd/m²]; E_V is the vertical eye illuminance [lux]; ω the solid angle of the window. The PGSV is the only index which accounts explicitly for the two causes of discomfort glare, namely the contrast and saturation glare.

The PGSV values are in the range from 0 to 3, meaning respectively just perceptible and just intolerable discomfort glare. The position index is not included in this formula because the glare source, thus the window, is expected to be always on the line of vision of the observer.

Wienold and Christoffersen (Wienold and Christoffersen 2006) also developed a discomfort glare index for daylighting, which is called the Daylight Glare Probability (DGP):

$$DGP = 5.87*10^{-5}E_V + 9.18*10^{-2}\log_{10}\left(1+\sum_{i=1}^{n}\frac{L_{s,i}^2*\omega_i}{E_V^{1.87}*P_i^2}\right) + 0.16 \quad (4)$$

where E_V is the vertical eye illuminance [lux]; $L_{s,i}$ the luminance of the glare source(s) [cd/m²]; ω_i the solid angle of the glare source(s); P_i the position index relative to the glare source(s).

The DGP, unlike other indices, expresses the probability that a person will be disturbed by glare. Its validated range goes from 0,2 to 0,8. A differentiating characteristic of DGP is that it uses the vertical illuminance at eye level as adaptation level. The formula is made of two main terms; the illuminance term standing for the saturation effect and the contrast term with the ratio between the glare sources and the adaptation level. The two terms will be analyzed in the following section.

These three indices are the most commonly used to predict discomfort glare from daylighting. They all have been developed through laboratory experiments. The experiment methodologies consist of asking the subjects to rate their perceived discomfort glare while measures of the luminous environment are taken. The parameters and the formula are defined to get the best correlation between the perceived and measured assessments of discomfort glare.

The same method, namely statistical inference, has been used so far to evaluate the influence of several factors on discomfort glare perception. To get rid of any interference between the studied factors, all the experimental conditions have to be controlled. This might be an important challenge when studying daylight glare from windows since daylight cannot be regulated. Similar lighting conditions can be achieved in laboratory experiments, by using a rotating cell (Rodriguez et al. 2016, Wienold and Christoffersen 2006), but hardly in field studies. Moreover, the notion of discomfort might be related to some psychological factors that, similarly, cannot be controlled. Another important issue of statistical analyses is the dependency of factors. Two factors are considered dependent on each other when the effect of one can be explained by the effect of the second. Therefore, only one of two dependent factors should be used as a variable influencing the perceived discomfort glare.

The factors later discussed in this paper are reported as having a potential influence on perceived discomfort glare. The criterion to discuss them is that at least one study investigated their effect, argumenting that the factor could have an influence on discomfort glare perception. But factors are not always studied under daylight conditions since some here-referenced experiments used artificial light or simulated windows as glare sources. The influence of a factor studied under artificial lighting conditions is assumed to be transferable to daylight conditions. Precautions should, however, be taken when interpreting the results as some studies (Borisuit et al. 2015, Laurentin et al. 2000) confirmed that people perceive discomfort glare differently whether it is from artificial lighting or daylighting.

All factors having been the object of at least one study as a potential variable of discomfort glare perception are reviewed and classified according to whether they are related to the lighting, to the context or to the observer. They are all listed in Tables 1 to 7, with the reference of the authors who investigated their effect on discomfort glare, listed in chronological order. To get a hint of the size of each study referenced, the *Subjects* column contains the number of subjects having taken part in the study. The *Evaluations* column gives the total number of glare evaluations if the study referenced is a field or laboratory experiment, namely a study involving subjective evaluations compared to physical measurements of glare. The total number of glare evaluations is the number of subjects times the number of condition(s) times the number of subjective glare evaluation(s) per condition. If the published study consists in a literature review or presents results from several past studies, an “R” letter is mentioned since the sample size and the number of glare evaluations cannot be displayed. If the study is based on a survey, which means that no measurements of glare are collected, an “S” letter is added next to the total number of participants in the survey. When the glare evaluation is made objectively, namely when glare perception is measured through a physiological response rather than evaluated by the subject (Iodice et al. 2017), an “O” letter is annotated. If the number of subjects, glare evaluations, or influence direction could not be determined from the publication, a “?” symbol is mentioned in place of the missing information. At last, a “P” letter means that the influence of the factor deduced from the publication does not refer to the study, but to the authors’ point of view.

Furthermore, the *Influence* column indicates whether an influence of the factor on discomfort glare perception is endorsed (V) or denied (X) by the study referenced. For all studies supporting the influence of a factor, an additional information is given in the *Influence direction* column. This column gives an overview of the agreement rate on the direction of the influence (increase or decrease of discomfort glare perception). For instance, two "A" letters for two studies having investigated the same factor mean that the two studies agree that discomfort glare perception is reduced or increased by the factor at stake.

In addition, an *Influence indicator* is proposed by the authors to express the likelihood –or unlikelihood– of the influence of the factor on discomfort glare perception. This indicator is based on the number of studies supporting or rejecting the influence of the factor as well as the sample size of the experiments. For more than two studies investigating an influencing factor, the influence indicator is defined as follows (definition of "studies" and "large experiments" see below the listing):

- almost certain if:
  ≥ 5 large experiments support the influence with a similar meaning
  & ≥ 10 studies support the influence with a similar meaning
  & 0 large experiment rejects the influence
  & ≤ 1 study rejects the influence
- more likely if:
  ≥ 2 large experiments support the influence with a similar meaning
  & ≥ 7 studies support the influence with a similar meaning
  & ≤ 1 study rejects the influence
- somewhat likely if:
  ≥ 2 studies support the influence with a similar meaning
  & ≤ 1 study rejects the influence
- inconclusive if:
  any other case
- somewhat unlikely if:
  ≥ 2 studies reject the influence
  & ≤ 1 study supports the influence
- less likely if:
  ≥ 2 large experiments reject the influence
  & ≥ 7 studies reject the influence
  & ≤ 1 study supports the influence
- almost certainly null if:
  ≥ 5 large experiments reject the influence
  & ≥ 10 studies reject the influence
  & 0 large experiment supports the influence
  & ≤ 1 study supports the influence

"Studies" include review studies, surveys, field and/or laboratory experiments.
"Large experiments" include field and/or laboratory experiments with sample size of 30 subjects or more.

For factors investigated by only one or two studies, the categories of the influence indicator have been defined as follows:

- somewhat likely if:
  ≥ 1 study support the influence with a similar meaning
  & 0 study rejects the influence
- inconclusive if:
  any other case
- somewhat unlikely if:
  ≥ 1 study reject the influence

& 0 study supports the influence.

This influence indicator is suggested in order to summarize the information and help define a prioritization list for future research. However, other characteristics than the sample size of the referenced studies should obviously be taken into consideration for the evaluation of the relevance of a study, such as the design of the experiment, the accuracy of the measurements, or the statistics. Since this information is either not available or not applicable for an objective comparison, the sample size was used as the only characteristic representative of the study relevance. This influence indicator should therefore be used with awareness of its restrictions and the classification into categories should not be interpreted as definitive or exclusive.

3. Description of daylight discomfort glare factors

3.1. Related to the lighting

3.1.1. Lighting environment

3.1.1.1. Luminance of the glare source

As stated previously, the luminance of a glare source is the source intensity in the observer viewing direction per unit area of the source. From the beginning, experiments conducted to better understand the basic factors of discomfort glare determined the glare source brightness to be one of the major variables (Luckiesh and Guth 1949, Petherbridge and Hopkinson 1950). In his work to summarize the established facts on discomfort glare, Einhorn acknowledged that discomfort glare increases if the source luminance increases (Einhorn 1969, 1979). A study of Ngai and Boyce (Ngai and Boyce 2000) confirmed the influence of the glare source luminance some years later. More recently, a study from Völker et al. in road lighting confirmed one more time the influence of the luminance of the glare source on discomfort glare perception (Völker et al. 2017).

The luminance of the glare source has already been considered as a discomfort glare index on its own. In this case, it was stated that the higher the luminance of the source, the more glare will be perceived (Carlucci et al. 2015). Other studies looked at the validity of the luminance of the window as a discomfort glare index in daylighting (Van Den Wymelenberg and Inanici 2016, Wienold and Christoffersen 2006). Moreover, glare source luminance thresholds have been suggested in different studies (Bülow-Hübe 2008, Dubois 2001, Lee et al. 2007, Shin et al. 2012), but until now, there has been no universal agreement on these threshold values. The use of unique luminance thresholds as discomfort glare indices should, however, be disregarded. Despite the correlation existing between the luminance of the glare source and discomfort glare perception, the luminance of the glare source alone cannot predict discomfort glare properly since other factors, such as the adaptation level (see § 1.1.2), the solid angle of the glare source (see § 1.2.1) or its position in the field of view (see § 1.2.2) have been acknowledged to significantly influence discomfort glare perception.

In most of today's daylight glare indices, the luminance of the glare source is not the only variable needed to predict the visual discomfort due to glare but is certainly one of the most important. However, one essential aspect to pay attention to is the meaning of "the source" when we assess discomfort glare from daylight. The glare source is naturally thought to be the window when studying daylight glare. But some years ago, the most common interpretation of the daylight glare source was the luminance of the patch of sky seen through the window (Chauvel et al. 1982, Hopkinson 1972, Velds 2000). Another interpretation of the glare source luminance was the one of Tokura and Iwata who referred to the vertical luminance of the window measured at one point in the center of the window (Tokura et al. 1996). For the development of the China Glare Index (Huang and Wang 2016), Huang and Wang used the average luminance of the entire window. However, during the development of the DGP index, Wienold observed that the window luminance did not correlate with subjects' discomfort glare perception (Wienold 2009a). Therefore, the bright spots in the field of view exceeding four times the task area average luminance were used as glare sources instead of the window. The task area does not contain areas of the window or any potential glare source in this case.

The non-uniformity of the window luminance should also be taken into account. The luminance distribution on a window plane will never be uniform in the real world as some parts will always be slightly brighter than others, due to the position of the sun or the clouds. Some obstacles in front of the window can even create shadows, making the range of luminance on the window plane larger. The orientation of the room can also play a role in the non-uniformity of the window. According to the orientation and latitude of a building, more direct sunlight will hit some of the building facades while other facades will never endure direct sun rays. In a Dutch office building, subjects reported more discomfort glare from windows facing South than East or West. The north orientation was the one causing the least problems with discomfort glare due to direct sunlight (Hellinga 2013). Moreover, several studies have pointed out that perceived discomfort glare from non-uniform sources is different than from uniform sources. Waters et al. observed that when a subject looks directly to a glare source, non-uniform sources are perceived as more glaring than uniform sources. On the contrary, when the glare source is in the observer's periphery, non-uniform sources are perceived as less glaring (Waters et al. 1995). Velds partly confirmed this observation as she noticed that when asking subjects to rank the perceived visual discomfort, discomfort glare from non-uniform sources was higher than from uniform sources with identical average luminance (Velds 2000). Moreover, in a study with real windows, N. Tuaycharoen pointed out that a view with a wide range of luminance would result in higher perceived discomfort glare than a more uniform view (Tuaycharoen and Tregenza 2007). On the opposite, E. Mochizuki observed in an experiment with a real window covered with a screen that large glare sources with a non-uniform luminance distribution induced less discomfort glare than uniform glare sources (Mochizuki and Iwata 2005). This finding was supported by Eble-Hankins and Waters, as in their experiment, non-uniform glare sources were rated as less discomforting than uniform glare sources (Eble-Hankins and Waters 2009). However, it was also concluded from that experiment that the contrast spatial frequency of the non-uniform glare sources had a significant effect on discomfort perception, and that this effect would vary according to the position of the glare source in the field of view. This last observation could be an explanation for the contradiction found between the different studies. More recently, several studies having observed an influence of the non-uniformity of artificial glare sources, such as LEDs, on discomfort glare perception, are working on modifications and alternatives of the Unified Glare Rating (UGR) index for non-uniform light sources (Cai and Chung 2012, Donners et al. 2016, Geerdinck et al. 2014, Scheir et al. 2015, Scheir et al. 2017, Tashiro et al. 2015, Yang et al. 2017). Hence, the non-uniformity of a window should be taken into account, excluding the average luminance of the window as the luminance of the glare source definition.

Currently, glare sources in a daylit scene are generally defined as the bright spots in the field of view. The challenge still lies in the definition of an objective and universal method to identify these spots (Clear 2013). A first method was implemented in findglare (Ward 1993). This method identifies as glare sources every spot in a High Dynamic Range (HDR) image being seven times higher than the average luminance of this image. More recently, another method was developed by Wienold and Christoffersen to identify glare sources (Wienold and Christoffersen 2006). The algorithm of the tool Evalglare recommended for typical office situations calculates the average luminance of a given zone, such as the task area, from an HDR image and points up the spots having luminance x-times higher than the average luminance of the reference zone (Wienold 2009b). The task zone should not contain areas of the window and, therefore implicitly, any other potential glare source. These spots can then be evaluated as glare sources.

The most advanced and reliable determination method of glare sources seems to be so far the task-threshold-method. This is partly due to the fact that this method takes into account the adaptation process of the eye, but also considering that in a daylit environment, not only the window can be a source of glare. Daylight reflections might also generate discomfort and should therefore be considered as glare sources as well. This method can, however, lose robustness when the glare source is within the defined task area, which was explicitly excluded in the original publication of Wienold and Christoffersen (Wienold and Christoffersen 2006). In this case, the glare identification threshold is dramatically increased and the method was demonstrated as being not sensitive enough for glare sources detection (Van Den Wymelenberg and Inanici 2014). This could be solved by applying other identification methods in this particular situation, such as a fixed glare identification threshold. Moreover, the task-

threshold-method requires the arbitrary definition of a "threshold multiplier", namely a factor by which the average luminance of the task area has to be multiplied to set the glare detection threshold. Depending on the choice of this threshold, the results of some of the glare metrics were shown to vary significantly (Sarey Khanie et al. 2015).

In conclusion, the influence of the glare source luminance on perceived discomfort glare is not a matter of debate anymore. Recent studies confirm the high correlation existing between the luminance of a glare source and the perceived degree of discomfort glare (Chen et al. 2015, Huang et al. 2017, Lin et al. 2014, Rodriguez and Pattini 2014, Tyukhova 2015), although this correlation is not large enough to explain discomfort glare perception in entirety. The glare source luminance is the most decisive factor when assessing discomfort glare, but should not be used as a discomfort glare index on its own. This is due to the other factors playing a role in discomfort glare perception, such as the adaptation level. Moreover, the existing and commonly applied methods to detect glare sources nowadays lack robustness when applied to glare metrics only relying on glare sources. Further research is therefore needed to clarify the definition of discomfort glare sources. In the meanwhile, an efficient way of validating the glare sources detection made by an algorithm is by examining each image visually.

3.1.1.2. Adaptation level

The adaptation level can be defined as the light level in a room which sets the adaptation of the eyes to the luminous environment. According to the lighting conditions, the pupil either constricts or dilates, regulating the intensity of light coming on the retina.

Stringham et al. investigated the effect of subject's pupil diameter on discomfort glare perception of twenty-six subjects and found out a negative relationship between the two (Stringham et al. 2011). The statistical results indicated that the smaller the pupil diameter was, the higher the discomfort glare was perceived, despite a smaller amount of light reaching the retina. This last result might be paradoxical as it can be assumed that the wider the pupil diameter, the larger the amount of light entering the eyes and the higher the perceived discomfort glare. But the variation of the pupil size should not be looked at as a cause of discomfort glare but as a consequence. The pupil diameter responds to the surrounding luminous conditions. Therefore, when the light in the field of view is very bright, the pupil diameter tends to narrow and filter the amount of light in order to protect the retina.

To allow the eye to adjust to the lighting conditions, a certain time, called the adaptation time, is needed. Hopkinson was the first to study whether the duration of exposure to a glare source has an influence on discomfort glare perception (Hopkinson 1957). The results of his experiment showed that momentary exposure produced more discomfort from glare than continuous exposure. This is not surprising since the momentary exposure in this study was only a few seconds long, which is a very short adaptation time. The duration time of exposure to large glare sources was studied by Iwata et al. in an experiment with a simulated window (Iwata et al. 1990). They observed that a glare source was already perceived as less glaring thirty seconds after exposure than immediately after it. Sivak et al. also studied the influence of exposure duration on discomfort glare perception in road lighting (Sivak et al. 1997). They observed that the longer was the exposure duration –with the shortest exposure being 0.125 and the longest 2 seconds-, the higher was the glare rating. More recently, in a study of Geerdinck, it was observed that the first assessment of glare was generally a good predictor for the glare perception after one hour, suggesting that a very long exposure time would not influence discomfort glare perception (Geerdinck 2012). This is the reason why in all subjective glare assessment experiments, subjects should be given some time to adapt to ambient lighting conditions.

Two physical quantities have been used to evaluate the adaptation level in discomfort glare indices: the vertical illuminance at eye level and the background luminance.

- Vertical illuminance at eye level

The illuminance is the total amount of the luminous flux reaching a surface, related to the surface area. The vertical illuminance at eye level provides a measure of the amount of light reaching the eyes of the observer. When included in a metric to stand for the adaptation level, the vertical illuminance takes into account the glare sources.

The CIE Glare Index (CGI) was the first glare metric to include the term of vertical illuminance at eye level instead of background luminance as the adaptation level (Einhorn 1979). The illuminance of the scene was also used as an independent variable to evaluate discomfort glare in a study of Ngai and Boyce instead of the background luminance (Ngai and Boyce 2000). More recently, the vertical illuminance at eye level was referred to in the DGP formula (Wienold and Christoffersen 2006). The illuminance is included in the denominator of the contrast term to account for the adaptation level.

- Background luminance

The background luminance, although more often used in the beginning of discomfort glare research than the vertical illuminance, has been a controversial factor due to the uncertainty about its determination. The CIE definition of the background luminance is "*the uniform luminance of the whole surroundings which produces the same illuminance on a vertical plane at the observer's eye as the visual field under consideration excluding the glare sources*" (CIE 1995). But in the literature, the definition of the background luminance is not always explicit and might be interpreted differently.

Luckiesh and Guth first studied the effect of adaptation level by using an "*extended visual field of uniform brightness"* named the field brightness (Luckiesh and Guth 1949). In Petherbridge and Hopkinson's first laboratory experiment on discomfort glare (Petherbridge and Hopkinson 1950), the adaptation level is defined as the "*general background brightness of the surroundings*", which may suggest that the glare sources are included. Later, Hopkinson invoked the "*surround luminance*" as the adaptation level in an expression assessing discomfort glare (Hopkinson 1957). Although no clear explanation is given to determine this surround luminance, it can be deduced that it excludes the glare sources. In the Daylighting book, the background luminance is referred to in the glare index as the luminance of the adapting visual field, which is a "*function of the average luminance of the room interior*" (Hopkinson et al. 1966). In a later expression of the glare index, the background luminance is further defined by Hopkinson as "*the average luminance of the visual field in which the glare sources are seen*" (Hopkinson 1972). In the current version of DGI by Chauvel et al., the background luminance is referred as "*the average luminance of the interior surfaces of the room which contribute to the visual field of an occupant of the room*" (Chauvel et al. 1982). From the explanations provided in the appendices of this last reference to measure the background luminance, the glare sources are assumed as not being included in the background luminance evaluation. On the other hand, Hopkinson and Chauvel et al. also mentioned that besides the background luminance, the window luminance should be added in the denominator of the glare index expression, since "*the light from the large glaring light source is seen itself to affect the average luminance of the visual field*" and therefore increase the adaptation of the eye (Chauvel et al. 1982, Hopkinson 1972). In a study on discomfort glare from daylight, Tokura et al. resorted to the background luminance as the average luminance in the field of view deduced from the vertical illuminance at eye level, minus the luminance of the window (Tokura et al. 1996). On the other hand, when working on a new version of the DGI index, Nazzal recommended the use of the "*adaptation luminance*" instead of background luminance (Nazzal 2005). In this case, the adaptation luminance includes the luminance of the window and is evaluated from the vertical illuminance. Kim and Koga recommended the use of the immediate background luminance, defined as "*the luminance of the local background containing the source when the entire background consists of numerous local backgrounds*" instead of the background luminance (Kim and Koga 2004). In road lighting, the average luminance of the road seems to be used as the adaptation luminance, although this is refuted by Völker et al. (Völker et al. 2017).

Besides the fact that there is some confusion about what should be evaluated as the background luminance (Clear 2013), authors seem to disagree on the importance of its effect on discomfort glare perception. In a study with real windows, Iwata made the assumption that background luminance had a

small influence on the degree of discomfort glare (Iwata et al. 1992b). Moreover, Saur could not observe any influence of an increased background luminance on discomfort glare perception (Saur 1969). On the other hand, Kim and Koga concluded from their laboratory experiment on discomfort glare that "*the background luminance is one of the main factors affecting the degree of discomfort glare*" (Kim and Koga 2004). They added that the threshold luminance bearable for the subjects was mainly determined by the immediate background luminance. Recent studies also confirmed that discomfort glare perception can be significantly decreased with the addition of a luminous surround (Lin et al. 2014, Sweater-Hickcox et al. 2012).

Although nowadays, the background luminance is generally interpreted as the average luminance of the visual field excluding the glare sources (Bellia et al. 2008, Cantin and Dubois 2011, Carlucci et al. 2015, Jakubiec and Reinhart 2011, Kent 2016, Tyukhova 2015), other interpretations of this background luminance still occur, such as the average luminance of the visual field including the glare sources (Huang and Wang 2016), or the average luminance of the visual task (Hirning et al. 2014). There is thus a need to clarify what exactly the background luminance is.

The CIE defines the background luminance as the indirect vertical illuminance at eye level divided by π (CIE 1995). Kim and Kim used a similar definition of the background luminance –replacing the indirect vertical illuminance by the total vertical illuminance- as an estimation of the average luminance of the field of view (Kim and Kim 2012). However, per definition, the vertical illuminance considers the cosine of the angle of incidence. Therefore, CIE definition is mathematically not equal to the background average luminance due to the ponderation with the cosine of the angle of incidence. For "almost homogeneous background" environments, the difference between the mathematical average and the CIE definition is small, and in practice, without impact. But it should be noted that software tools may calculate the background average luminance differently (e.g. by calculating the mathematical average luminance without ponderation with the cosine of the angle of incidence). From the CIE definition of the background luminance, it follows that the main difference between the vertical illuminance at eye level and the background luminance is the inclusion or exclusion of the glare sources in the evaluation of the term. Moreover, in most discomfort glare indices for large glare sources using the background luminance, the luminance of the glare source is added in the denominator with a certain weight to account for its effect on the observer's eyes adaptation. Therefore, in practice, both methods are similar, except for the weighting of the glare source luminance and the π constant. Fisekis et al. compared the DGI values for two interpretations of the background luminance, namely on one hand the average luminance excluding the glare sources, and, on the other hand, the average luminance of the whole surroundings given by the division of the vertical illuminance by π (Fisekis et al. 2003). Although the double contribution of the source in the adaptation term was considered as a theoretical issue when using the second interpretation, it was concluded that excluding the glare source from the background luminance offered a better prediction of subjects' discomfort glare assessments.

In conclusion, what should be taken into consideration is that large glare sources covering a wide area in the field of view will change the adaptation level. The adaptation level of the eyes in the case of small sources is mainly influenced by the background luminance. In the case of large sources, the interaction of the glare source and the surroundings plays a role in the eyes adaptation process, as explained by Petherbridge and Hopkinson in 1950 (Petherbridge and Hopkinson 1950). In the current version of PGSV index, both approaches are used (Iwata et al. 2011b); on one hand, the background luminance excluding the glare sources is used in the term representing the contrast glare, and on the other hand, the adaptation luminance, evaluated from the vertical illuminance including the glare sources, is used in the term for the saturation glare type.

3.1.1.3. Contrast effect

One of the two types of discomfort glare is due to the contrast between the glare source and the adaptation level. Hopkinson came to this conclusion years before, distinguishing the contrast effect leading to the relative discomfort glare from the saturation effect leading to the absolute discomfort glare (Hopkinson et al. 1966). In most of current discomfort glare indices, the contrast effect is expressed as

a ratio. The ratio between the glare source luminance and the adaptation level appears for instance in DGI (Chauvel et al. 1982), PGSV (Iwata et al. 2011b) and DGP (Wienold and Christoffersen 2006), often associated with the solid angle of the glare source (§ 1.*ii*.a) and the position index (§ 1.*ii*.b).

Chauvel et al. acknowledged the interaction between the luminance of the sky and that of the surroundings as being one of the two most important parameters in the assessment of glare from windows (Chauvel et al. 1982). Recently, Hirning et al. recommended the use of the ratio between the background and the window (Hirning et al. 2017) as this ratio is said to be a more sensitive parameter of discomfort glare perception than the ratio between the window and the task. On the other hand, a study based on a re-evaluation of an existing dataset suggests that there are certain definitions of luminance ratio, for instance the luminance ratio between the task area and the immediate surround, which have better correlations with subjective glare assessments in offices with daylighting (Hansen et al. 2016). In Carlucci et al.'s review of glare indices, the luminance ratio between the central zone of the field of view and the surroundings represents a discomfort glare index in itself (Carlucci et al. 2015). In the case of core zones of open-plan offices where discomfort glare is mainly due to contrast, it was also demonstrated that the ratio between maximum window luminance and visual task luminance performed much better at predicting discomfort glare than any other glare metrics (Konis 2014). Moreover, several studies have been carried out to determine the maximum luminance ratio between the source and the background in order to prevent discomfort glare (Linney 2008, Osterhaus 2009, Veitch and Newsham 2000).

3.1.1.4. Saturation effect

The second type of discomfort glare, the absolute glare, is occurring when the amount of light of a glare source exceeds a certain threshold, inducing glare regardless of the contrast in the visual field. This saturation effect has often been evaluated by the vertical illuminance at eye level. Although this term was never included in the factors influencing the perceived discomfort glare by the CIE, it seems that some authors still relate eye illuminance to visual discomfort caused by glare.

In 1966, Bourassa and Wirtschafter concluded from an experiment that the discomfort glare threshold is directly linked to the total illuminance on the eyes (Bourassa and Wirtschafter 1966). Later on, Sivak et al. found out that illuminance at eye level strongly influences discomfort glare ratings (Sivak et al. 1989). Similarly, during an experiment on discomfort glare from a real window, Iwata et al. observed that the vertical illuminance at eye level, or the amount of light entering the eyes, had the largest effect on the glare sensation vote (Iwata et al. 1992b). Velds also found a good correlation between glare assessments and measured vertical illuminance orientated towards the window (Velds 2000). Kim and Kim used the illuminance at eye level to evaluate an average luminance in the visual field (Kim and Kim 2012). They observed that the logarithm value of the so-calculated average luminance was in proportional relationship with the perceived discomfort glare values from the entire window. Consequently, they proposed an equation to determine a glare threshold in which the only variable is the vertical illuminance at eye level. The DGP also includes a specific term representing the absolute glare with the vertical illuminance at eye level (Wienold and Christoffersen 2006). And the current PGSV index differentiates between contrast and saturation effects by offering two distinct expressions (Iwata et al. 2011b). In road lighting, the vertical illuminance has been several times acknowledged to be a significant variable influencing discomfort glare rating (Sivak et al. 1997, Völker et al. 2017).

To conclude this section, both glare types, the absolute and contrast glares, should be considered when evaluating glare from daylight. From the existing discomfort glare metrics, only PGSV and DGP are considering both types, either through two independent terms or with two different expressions. The DGI index, on the other hand, only considers the contrast effect. Therefore, it was demonstrated that when the glare source covers the entire field of view, DGI cannot properly predict discomfort glare (Inoue and Itoh 1989, Iwata and Tokura 1998). The issues of integration of both glare effects as well as source and background luminance distinction have already been discussed in the past (Clear 2013). Jakubiec and Reinhart also suggested that the prediction of visual discomfort should integrate several metrics since a single metric cannot cover all situations (Jakubiec and Reinhart 2016). Furthermore, in

the case of discomfort glare from daylight, more rigor regarding the definition of the glare sources and the adaptation level is required, as well as a deeper understanding of these terms.

Table 1. Factors related to the lighting environment having a potential influence on discomfort glare perception from daylight. *Author(s)/Year* = authors having studied the factor, classified by chronological order; *Subjects* = number of subjects having participated in the study; *Evaluations* = number of glare evaluations made during the study; *Influence* = detection or not of an influence of the factor on discomfort glare perception in the study; *Influence direction* = direction of the influence of the factor (increase or decrease of discomfort glare perception) –should be used to evaluate the agreement rate between studies–; *Influence indicator* = likelihood of the influence of the factor on discomfort glare perception.

Factor	Author(s)	Year	Subjects	Evaluations	Influence	Influence direction	Influence indicator
Luminance of the glare source	Luckiesh & Guth	1949	50	50	V	A	**ALMOST CERTAIN**
	Petherbridge & Hopkinson	1950	6	?	V	A	
	Einhorn	1969/1979	R	R	V	A	
	Hopkinson	1972	R	R	V	A	
	Chauvel et al.	1982	R	R	V	A	
	Waters et al.	1995	12	288	V	?	
	Tokura et al.	1996	240	2400	V	A	
	Ngai & Boyce	2000	16	1280	V	A	
	Velds	2000	84	656	V	A	
	Dubois	2001	R	R	V	A	
	Mochizuki & Iwata	2005	19	114	V	?	
	Lee et al.	2007	42	630	V	A	
	Tuaycharoen & Tregenza	2007	168	600	V	?	
	Bülow-Hübe	2008	R	R	V	A	
	Eble-Hankins & Waters	2009	67	1608	V	?	
	Wienold	2009a	76	349	V	A	
	Cai & Chung	2012	?	536	V	?	
	Shin et al.	2012	48	2400	V	A	
	Clear	2013	R	R	V	A	
	Hellinga	2013	558	S	V	?	
	Geerdinck et al.	2014	42	668	V	?	
	Lin et al.	2014	12	864	V	A	
	Rodriguez & Pattini	2014	25	200	V	A	
	Carlucci et al.	2015	R	R	V	A	
	Chen et al.	2015	8	576	V	A	
	Scheir et al.	2015	R	R	V	?	
	Tashiro et al.	2015	8	?	V	?	
	Tyukhova	2015	47	1692	V	A	
	Donners et al.	2016	82	NA	V	?	
	Huang & Wang	2016	R	R	V	A	
	Van Den Wymel. & Inanici	2016	48	1379	V	A	
	Huang et al.	2017	18	324	V	A	
	Scheir et al.	2017	20	1440	V	?	
	Völker et al.	2017	R	R	V	A	
	Yang et al.	2017	20	3120	V	?	
Adaptation level	Luckiesh & Guth	1949	10	30	V	A	**ALMOST CERTAIN**
	Petherbridge & Hopkinson	1950	6	?	V	A	
	Hopkinson	1957a	3	?	V	?	
	Hopkinson	1957b	R	R	V	A	
	Hopkinson et al.	1966	R	R	V	A	
	Einhorn	1969/1979	R	R	V	A	
	Saur	1969	?	168	X		
	Hopkinson	1972	R	R	V	A	
	Chauvel et al.	1982	R	R	V	A	
	Iwata et al.	1990	80	800	V	?	
	Iwata et al.	1992b	46	552	V	A	
	Tokura et al.	1996	240	2400	V	A	
	Sivak et al.	1997	16	1600	V	?	
	Ngai & Boyce	2000	16	1280	V	A	
	Fisekis et al.	2003	10	133	V	A	
	Kim & Koga	2004	25	375	V	A	
	Nazzal	2005	R	R	V	A	
	Wienold & Christoffersen	2006	76	349	V	A	
	Stringham et al.	2011	26	468	V	A	
	Geerdinck	2012	42	840	V	?	
	Sweater-Hickcox et al.	2012	10	200	V	A	
	Kim & Kim	2012	108	4428	V	A	
	Clear	2013	R	R	V	A	
	Lin et al.	2014	12	864	V	A	
	Tyukhova	2015	47	1692	V	A	
	Völker et al.	2017	R	R	V	A	

Contrast effect	Hopkinson et al.	1966	R	R	V	A	**ALMOST CERTAIN**
	Chauvel et al.	1982	R	R	V	A	
	Veitch & Newsham	2000	94	94	V	A	
	Wienold & Christoffersen	2006	76	349	V	A	
	Linney	2008	48	144	V	A	
	Osterhaus	2009	R	R	V	A	
	Iwata et al.	2011b	12	108	V	A	
	Konis	2014	14	523	V	A	
	Carlucci et al.	2015	R	R	V	A	
	Hansen et al.	2016	76	428	V	A	
	Hirning et al.	2016a	341	341	V	A	
Saturation effect	Bourassa & Wirtschafter	1966	3	15	V	A	**MORE LIKELY**
	Sivak et al.	1989	12	1080	V	A	
	Iwata et al.	1992b	46	552	V	A	
	Sivak et al.	1997	16	1600	V	A	
	Velds	2000	84	656	V	A	
	Wienold & Christoffersen	2006	76	349	V	A	
	Iwata et al.	2011b	12	108	V	A	
	Kim & Kim	2012	108	4428	V	A	
	Völker et al.	2017	R	R	V	A	

R = literature review S = survey O = objective glare rating P = authors' point of view ? = information not available X = no influence of the factor V = influence of the factor

3.1.2. Interaction between the observer and the glare source

3.1.2.1. Size of the glare source as seen by the observer

Although there is a clear definition of a glare source missing, the size of it is defined by the solid angle which expresses the width of the source as it appears to the observer eyes. Distance from the window is therefore impacting the way we perceive discomfort glare. The further away we are from the window, the smaller the solid angle subtended at the eye and the lesser is the perceived discomfort glare. Velds confirmed this effect in her PhD thesis as she observed that subjects at the back of the room felt in general less glare than the ones near the facade under similar lighting conditions (Velds 2000). Aries et al. also concluded from their survey on subject's well-being at work that the further the subject sat from the window, the more satisfied he/she was since he/she experienced less discomfort glare (Aries et al. 2010).

The solid angle has always been included in discomfort glare formulas to account for the apparent area of the glare source (Einhorn 1969, 1979, Luckiesh and Guth 1949, Petherbridge and Hopkinson 1950). Since a glare source is not clearly defined, this indistinctness impacts also the usage of the size of a glare source. Hopkinson mentioned the solid angle subtended by the patch of sky seen through the window to refer to the glare source size (Hopkinson 1972) and was followed by Chauvel et al. some years later (Chauvel et al. 1982). In the first version of the GSV index, the source size is evaluated as the solid angle subtended by the entire window to the point of observation (Tokura et al. 1996). In the DGP index, the solid angle of a glare source is the sum of the solid angle of the pixels in a HDR image belonging to this glare source (Wienold and Christoffersen 2006). As already mentioned, more research is required to build a robust method to define glare sources so that their luminance and solid angle can be evaluated accurately.

The solid angle of the glare source helps to describe the perceived degree of glare according to the distance of the observer from the source and the size of the source. It was assumed that discomfort glare perception has a negative linear relationship with the distance from the window and a bell-shaped relationship with the size of the window (Boubekri and Boyer 1992). Recently, Rodriguez and Pattini concluded from an experiment with a simulated window that the source size had the same impact on perceived discomfort glare than the luminance of the source (Rodriguez and Pattini 2014). Recent studies also confirmed that an increased solid angle produced more discomfort from glare (Lin et al. 2014, Tyukhova 2015).

3.1.2.2. Position of the glare source as seen by the observer

To account for the difference in the perception of a glare source in relation to its position in the field of view, the position index P was introduced by Luckiesh and Guth in their study on discomfort glare from small sources (Luckiesh and Guth 1949). The index is a function of the vertical and angular displacement of the source from the line of vision of the observer. Although Petherbridge and Hopkinson did not refer

to Guth position index in their experiments, they acknowledged the influence of the displacement of the source from the direction of view on discomfort glare perception (Petherbridge and Hopkinson 1950). Later, while Einhorn endorsed the position index as one of the four main variables influencing discomfort glare perception (Einhorn 1969, 1979), Hopkinson described it as a function of the angles between the direction of the light source and the observer's viewing direction (Hopkinson 1972). Whereas in Chauvel et al.'s DGI, the position index was determined thanks to the angles subtended by the glare source in the horizontal and vertical directions which were reported on a diagram (Chauvel et al. 1982). More recently, the vertical position of the glare source in the field of view was again acknowledged as influencing discomfort glare perception from laboratory studies (Chen et al. 2015, Eble-Hankins and Waters 2009, Huang et al. 2017, Lin et al. 2014, Tyukhova 2015). In road lighting as well, it was recognized that the larger the angle from the line of sight, the smaller the glare effect (Völker et al. 2017).

The PGSV index (Tokura et al. 1996) does not include the position index, which means that it only predicts discomfort glare perceived in the observer's line of sight. However, in a later study, Iwata and Tokura, investigated the difference between sensitivity to a glare source positioned above or below the line of vision (Iwata and Tokura 1997). They deduced, with the help of Einhorn, a new analytical equation applicable to glare sources located below the line of vision as they observed glare sensation was higher than when the source is in the upper part of the field of view. A modified position index was developed including two different expressions reflecting the upper and lower part of the field of view. The DGP index uses this modified position index (Wienold and Christoffersen 2006), namely Guth's position index for sources located in the upper part of the field of view and Iwata-Einhorn's for the lower part.

The glare source configuration, which, in the case of discomfort glare from daylight, might have been interpreted as the window configuration, should also be mentioned as a potential influencing factor. Although Chauvel et al. did not find an effect of windows shape on discomfort glare perception (Chauvel et al. 1982), Iwata et al. observed that a simulated rectangular window did not generate the same glare perception to the observers than a square simulated window, depending on the direction of the view (Iwata et al. 1992a). However, some years later, Hellinga confirmed that "*glare perception was not related to the different window configurations*" (Hellinga 2013).

The position of the glare source is considered as a factor influencing discomfort glare perception since existing literature agrees on the fact that the further the glare source from the line of vision, the less the perceived discomfort. Currently, Guth's position index is used in most existing glare metrics, for daylight and electric light. Further research on the combination of Guth's and Iwata-Einhorn's position index would be needed to confirm its validity. Recently, several laboratory studies (Kim et al. 2009, Kim and Kim 2010, 2011, Kim and Koga 2005) were conducted to develop a new position index in which the difference between sensitivity to a glare source positioned above or below the line of vision is implemented. However, there is an inconsistency between the formula and the graph published.

Table 2. Factors related to the interaction between the observer and the glare source having a potential influence on discomfort glare perception from daylight. *Author(s)/Year* = authors having studied the factor, classified by chronological order; *Subjects* = number of subjects having participated in the study; *Evaluations* = number of glare evaluations made during the study; *Influence* = detection or not of an influence of the factor on discomfort glare perception in the study; *Influence direction* = direction of the influence of the factor (increase or decrease of discomfort glare perception) –should be used to evaluate the agreement rate between studies–; *Influence indicator* = likelihood of the influence of the factor on discomfort glare perception.

Factor	Author(s)	Year	Subjects	Evaluations	Influence	Influence direction	Influence indicator
Size of the glare source as seen by the observer	Luckiesh & Guth	1949	10	50	V	A	**ALMOST CERTAIN**
	Petherbridge & Hopkinson	1950	6	?	V	A	
	Einhorn	1969/1979	R	R	V	A	
	Hopkinson	1972	R	R	V	A	
	Chauvel et al.	1982	R	R	V	A	
	Boubekri & Boyer	1992	40	40	V	A	
	Tokura et al.	1996	240	2400	V	A	
	Velds	2000	84	656	V	A	
	Wienold & Christoffersen	2006	76	349	V	A	
	Aries er al.	2010	333	S	V	A	
	Lin et al.	2014	12	864	V	A	
	Rodriguez & Pattini	2014	25	200	V	A	
	Tyukhova	2015	47	1692	V	A	
Position of the glare source as seen by the observer	Luckiesh & Guth	1949	10	270	V	A	**ALMOST CERTAIN**
	Petherbridge & Hopkinson	1950	6	?	V	A	
	Einhorn	1969/1979	R	R	V	A	
	Hopkinson	1972	R	R	V	A	
	Chauvel et al.	1982	R	R	V	A	
	Iwata & Tokura	1997	71	2130	V	A	
	Kim & Koga	2005	25	2400	V	A	
	Wienold & Christoffersen	2006	76	349	V	A	
	Eble-Hankins & Waters	2009	67	1608	V	A	
	Kim et al.	2009	27	1053	V	A	
	Kim & Kim	2010	32	2144	V	A	
	Kim & Kim	2011	8	1536	V	A	
	Lin et al.	2014	12	864	V	A	
	Chen et al.	2015	8	576	V	A	
	Tyukhova	2015	47	1692	V	A	
	Huang et al.	2017	18	324	V	A	
	Völker et al.	2017	R	R	V	A	

R = literature review S = survey O = objective glare rating P = authors' point of view ? = information not available X = no influence of the factor V = influence of the factor

3.2. Related to the context

3.2.1. Environment characteristics

3.2.1.1. Spectrum and color temperature

As the spectral power distribution or the correlated color temperature of daylight can vary with the type of glazing, as well as the weather and time of the day, it is worth studying the influence of these parameters on discomfort glare perception.

As a matter of fact, it has been demonstrated several times that the color temperature of the light could have an impact on discomfort glare perception. In several experiments on car headlights and on LED lights, the glare source or the background color was shown to have a significant influence on discomfort glare perception, as blueish light was always perceived as more discomforting (Berman et al. 1995, Flannagan 1999, Kimura-Minoda and Ayama 2011, Sivak et al. 2005, Sweater-Hickcox et al. 2012, van Bommel 2015, Yang et al. 2016). Moreover, some authors have reinforced this observation by showing that glare sources with a large amount of short-wavelengths resulted in higher perceived discomfort glare (Akashi et al. 2013, Bullough 2009, Fekete et al. 2009, Sivak et al. 2005, Stringham et al. 2003, Yang et al. 2016). However, it has recently been demonstrated that metameric light sources, namely sources having different spectral power distributions but the same correlated color temperature, did not lead to different discomfort glare perceptions (Huang et al. 2017). This last observation implies that the spectral power distribution is not directly influencing discomfort glare perception, but the correlated color temperature is. The influence of the correlated color temperature of the light, namely the apparent color of the light, on discomfort glare has recently been demonstrated again in several studies (Chen et al. 2015, Lin et al. 2014, Völker et al. 2017, Wei et al. 2014, Zhang et al. 2013). But one study from Ko and Choi could not observe an influence of the color temperature of the glare source on discomfort glare perception (Ko and Choi 2017).

Subsequently, glazing that filters some parts of the daylight spectrum causing it to appear colored, such as electrochromic glazing, might have an influence on discomfort glare perception. More research is required to extend the results of these studies on artificial glare sources for discomfort glare from filtered daylight.

3.2.1.2. View direction and position

By changing our view direction or our position, the luminance distribution across the field of view is altered. Some researchers currently focus on integrating this new variable by developing either view-independent or gaze-driven glare evaluation methods. The influence of view direction and position of the subject on his or her discomfort glare perception has indeed already been observed (Hirning et al. 2016, Sekihara et al. 2016).

The first step to take into account view direction into discomfort glare evaluation was made by Jakubiec and Reinhart with the 'adaptive zone' (Jakubiec and Reinhart 2011). They concluded that for one workplace, only one glare prediction should be considered, which is the lowest glare prediction in either of all directions. This is due to the fact that an occupant will select the least disruptive view direction and position within the adaptive zone to minimize the occurrence of discomfort glare for a particular workplace (Jakubiec and Reinhart 2016). Another study, using only simulations and no subjective glare evaluations, proposed a new glare evaluation method which should yield comparable results to the DGP-based approach (Torres and Lo Verso 2015). This new evaluation is based on the cylindrical illuminance, namely the average of all vertical illuminances in all directions around a considered point, and has therefore the advantage of making the glare analysis view-independent. Vasquez et al. looked at the time spent by a subject in several view directions and the corresponding glare metrics values (Vásquez et al. 2016). Although they could not find any relationship between the two –probably due to the other factors influencing the view direction such as the visual interest–, they observed that the subject seemed to alternate the sight between more and less stressful view scenarios. At last, a study from Sarey Khanie et al. used a more sophisticated method with a mobile eye tracker and 270° HDR images in order to derive a gaze-centered luminance map (Sarey Khanie et al. 2017). A significant difference was noticed between the gaze-driven and fixed-gaze glare evaluation method when participants' gaze was exploring the surroundings independently of the task. In the case of a scene with high luminance values, the view seems to avoid extreme regions containing discomfort glare. At last, a recent study from Iwata et al. showed that there was no difference in discomfort glare perception according to the position of the subjects towards the window –facing or perpendicular– (Iwata et al. 2017a).

As these studies are quite recent, more insight is needed on the influence of gaze and position on discomfort glare perception. Also, a comparison between gaze-driven or view-independent glare evaluation methods would be necessary as it was acknowledged in the case of road lighting that glare evaluation methods with a fixed view lead to higher glare rating than methods with a free view (Völker et al. 2017).

3.2.1.3. Attractiveness of the view through the window

As mentioned years ago, the view through the window affects the judgment of discomfort glare from windows (Chauvel et al. 1982). *"There is an underlying conflict in making an assessment in a highly glaring situation if the window has a pleasant view or one with a great deal of interesting information*" (Hopkinson 1972).

One of the first authors who showed a real effect of the view through the window on discomfort glare perception is Osterhaus (Osterhaus 2001). During a study conducted to identify the factors playing a role in the assessment of visual comfort in daylit office spaces, it was deduced from the results that discomfort glare might be less of an issue when there is an appealing view through the window. Likewise, Tuaycharoen and Tregenza conducted a large study on the effect of the view on perceived discomfort glare from windows (Tuaycharoen and Tregenza 2005). Their experiments showed that the tolerance to discomfort glare is increased when the source is an interesting image rather than a blank screen, and especially increased when the view contains elements of natural scenes instead of urban or man-made views. In order to validate their results, they conducted their experiments with real windows and under real daylighting conditions (Tuaycharoen and Tregenza 2007). They concluded that the best ranked view, namely the most attractive one, is significantly less glaring than the last ranked one which, in turn, is less glaring than the blank view. Moreover, views with natural scenes appeared to be

significantly less glaring than urban views and views with only one 'distance layer' produced more glare than views with three 'distance layers'. A last experiment of Tuaycharoen at Naruesan University in Thailand produced similar conclusions (Tuaycharoen 2011).

More authors studied the influence of window views on discomfort glare perception. Shin et al. observed from an experiment with a simulated window that tolerance to discomfort glare was higher for distant views including the sky layer than for near views and, surprisingly, lower for natural views than for man-made or urban views (Shin et al. 2012). From these observations, a new model to predict discomfort glare was suggested in which four characteristics of the view were included (Kim et al. 2012). Hellinga concluded in her PhD thesis that "*the outside view might only affect the perceived amount of glare if it is very good or very bad, because otherwise other variables play a more important role*" (Hellinga 2013) as no statistically significant correlation was found between occupant's subjective impression of an outside view and their sensation of glare. Similarly, in two other studies on discomfort glare under daylight conditions (Hirning et al. 2014, Iwata et al. 2017a), no statistically significant correlation was found with the view attractiveness. Since many subjects were satisfied with their view content, this lack of expected result could be interpreted in the same way as in Hellinga's thesis, which means that the view through the window only influences discomfort glare sensation when it is very good or very bad.

What should also be considered is the impact that the view through the window can have on the subject's acceptance towards discomfort glare. Wienold noticed during his PhD experiment that the acceptance of discomfort glare could increase in order to maintain the view although discomfort glare perception remains the same (Wienold 2009a). Therefore, shading controls strategies should be implemented in such a way that blinds do not block the view to the outside in order for the observers to keep a visual contact with the exterior (Iwata et al. 2017b).

To conclude, the view through the window has a direct influence on the acceptance and perceived degree of discomfort glare, especially when the observer has a strong opinion about it. Nonetheless, two characteristics of the view should be taken into account: the interest and the extent of the view.

3.2.1.4. Room temperature

To date, only one study focuses on the influence of thermal comfort on discomfort glare perception in office environments. The results of this experiment (Yamin Garretón et al. 2015) showed that the subjects had a different tolerance towards discomfort glare when they were outside their thermal comfort zone. In a study on the interaction of comfort parameters (Laurentin et al. 2000), no influence of thermal conditions on visual discomfort could be found in the case of daylighting. However, the lack of effect might be due to the fact that the maximum temperature in the study was only 3°C above the thermal comfort zone (Inkarojrit 2005).

Our perception of discomfort glare could also be influenced by other discomfort parameters such as humidity or noise. More research is needed to define these interactions properly.

Table 3. Factors related to the environment characteristics having a potential influence on discomfort glare perception from daylight. *Author(s)/Year* = authors having studied the factor, classified by chronological order; *Subjects* = number of subjects having participated in the study; *Evaluations* = number of glare evaluations made during the study; *Influence* = detection or not of an influence of the factor on discomfort glare perception in the study; *Influence direction* = direction of the influence of the factor (increase or decrease of discomfort glare perception) –should be used to evaluate the agreement rate between studies–; *Influence indicator* = likelihood of the influence of the factor on discomfort glare perception.

Factor	Author(s)	Year	Subjects	Evaluations	Influence	Influence direction	Influence indicator
Spectrum and color temperature	Berman et al.	1995	12	1080	V	A	**MORE LIKELY**
	Flannagan	1999	12	288	V	A	
	Stringham et al.	2003	3	33	V	A	
	Sivak et al.	2005	12	540	V	A	
	Bullough	2009	67	934	V	A	
	Fekete et al.	2009	10	2200	V	A	
	Kimura-Minoda & Ayama	2011	15	1395	V	A	
	Sweater-Hickcox et al.	2012	10	200	V	A	
	Zhang et al.	2013	18	180	V	A	
	Lin et al.	2014	12	864	V	A	
	Wei et al.	2014	26	S	V	A	
	Chen et al.	2015	8	576	V	A	
	van Bommel	2015	R	R	V	A	
	Yang et al.	2016	20	960	V	A	
	Huang et al.	2017	18	324	V	A	
	Ko & Choi	2017	176	1760	X		
	Niedling & Völker	2017	36	648	V	A	
	Völker et al.	2017	R	R	V	A	
View direction and position	Jakubiec & Reinhart	2015	194	S	V	A	**INCONCLUSIVE**
	Hirning et al.	2016b	49	68	V	?	
	Khanie et al.	2016	97	97	V	A	
	Sekihara et al.	2016	20	240	V	?	
	Vasquez et al.	2016	1	12	V	B	
	Iwata et al.	2017	146	584	X		
	Völker et al.	2017	R	R	V	A	
Attractiveness of the view through the window	Hopkinson	1972	R	R	V	A	**INCONCLUSIVE**
	Chauvel et al.	1982	R	R	V	?	
	Osterhaus	2001	83	S	V	A	
	Tuaycharoen & Tregenza	2005	32	1152	V	A	
	Tuaycharoen & Tregenza	2007	168	600	V	A	
	Wienold	2009a	76	349	V	A	
	Tuaycharoen	2011	76	752	V	A	
	Shin et al.	2012	48	2400	V	A	
	Hellinga	2013	558	S	X		
	Hirning et al.	2013a	468	493	X		
	Iwata et al.	2017	146	584	X		
Room temperature	Laurentin et al.	2000	20	180	X		**INCONCLUSIVE**
	Yamin Garretón et al.	2015	19	57	V	A	

R = literature review S = survey O = objective glare rating P = authors' point of view ? = information not available X = no influence of the factor V = influence of the factor

3.2.2. Glare experiment characteristics

3.2.2.1. Time of the day

Depending on the time of the day, our sensation of discomfort glare might be fluctuating. It was first demonstrated by two studies conducted under artificial lighting conditions that as the day progresses, tolerance towards discomfort glare increases (Altomonte et al. 2016a, 2016b, Kent et al. 2015a, Kent et al. 2015b). On the opposite, a study conducted by Borisuit et al. revealed no evolution of perceived glare sensation for a period of eight hours (Borisuit et al. 2015). However, no neutral basis was defined to compare the subjective glare evaluations made during the day in this last study as daylight might have been changing but no discomfort glare index was calculated. Recently, Kent et al. conducted another study under daylighting conditions to confirm the effect of time of day on discomfort glare perception (Kent et al. 2017a). They concluded that the time of the day could be one of the causes explaining the large variability between subjects' discomfort glare perception, since a statistically significant influence of this factor was observed.

3.2.2.2. Season

A seasonal effect on discomfort glare perception means that depending on the season and its related daylight characteristics, tolerance towards discomfort glare might vary.

Some authors have already suggested that subjects have a higher acceptance of the presence of sunlight in winter than in summer (Christoffersen et al. 2000, Nicol et al. 2006). In one of Van Den Wymelenberg's experiments on discomfort glare, participants were significantly more sensitive to glare source brightness during fall than during summer, with a difference of approximately 100 cd/m² in glare source luminance (Van Den Wymelenberg 2012). This effect could, however, also be attributed to post-awake sunlight availability, namely a smaller or larger amount of daylight prior to the experiment.

Since only one study could find an influence of seasons on discomfort glare perception, and since the seasonal influence might overlap with previous luminous environment (§ 3.*iii*.a), more research is required to conclude on the influence of this factor.

3.2.2.3. Task difficulty

Quite often, attention tasks, such as the Stroop test (MacLeod 1991), are used to assess the influence of the visual environment on workers' productivity and concentration. However, some studies (Flannagan et al. 1990, Sivak et al. 1989) have shown that the task required while rating the visual environment could impact this rating. It is thus important to determine whether the perceived discomfort glare is influenced by the presence and the difficulty of a task, or the other way around.

Sivak et al. concluded from an experiment on the influence of a visual task on discomfort glare ratings (Sivak et al. 1989) that more difficult tasks resulted in more discomforting glare responses, and that the effect was more noticeable at low levels of glare. Flannagan et al. conducted another experiment to extend these findings (Flannagan et al. 1990). Besides reinforcing Sivak et al.'s results on task difficulty, they showed that when subjects have to accomplish a visual task, perceived discomfort glare tends to be higher than when no task is required. On the opposite, Osterhaus and Bailey observed in a study on the effects of large area glare sources on discomfort glare perception that when a task was required, subjects tended to be less sensitive towards discomfort glare (Osterhaus and Bailey 1992). A recent study from Altomonte et al. demonstrated that the more difficult the visual task was, the higher the glare sensation was perceived (Altomonte et al. 2016a, 2016b). This effect was noticed to be more significant at earlier sessions during the day, although the authors warned on the potential interaction between temporal variables which could have affected the variation of glare response as the day progresses since a direct relationship was also found between fatigue and glare response. In road lighting, the influence of the task difficulty on discomfort glare perception has been recognized, although it is not yet sure whether more difficult tasks generate higher or lower discomfort glare perception (Völker et al. 2017).

In the mentioned studies, glare assessments usually take place after the subjects have finished their task – not during the task itself. In addition to the need for further research on the influence of task difficulty on discomfort glare perception, discomfort glare assessments acquired from subjects while they are performing a task should be investigated against others acquired after the task.

3.2.2.4. Glare rating scales and experimental design

Discomfort glare is almost never assessed objectively – its evaluation is, up to now, mainly relying on feedback by the use of questionnaires. The subject is asked to evaluate his or her perception of discomfort glare through rating scales, such as the De Boer scale (De Boer 1967), Hopkinson's scale (Hopkinson 1971) or the Glare Sensation Vote (Iwata et al. 1992a). Several distortions can occur due to these rating scales or to the way the experiment is designed:

- bias towards higher glare assessments

Scales used to evaluate discomfort glare might lead the subject to acknowledge the presence of glare since "no glare" is often not a choice in the available responses on the rating scale (Fotios 2015). Subjects' answers are thus biased as the reported stimulus is somehow imposed. Moreover, when asking questions about glare itself, the attention is drawn on it, forcing the glare option (Van Den Wymelenberg 2014). The act of asking subjects to rate their discomfort glare may incite them to acknowledge something they would not have considered in other conditions.

- interpretation of scale labels

The various labels of existing rating scales may be interpreted in different ways, either between different subjects participating in a survey or between researchers using the scale labels differently (Fotios 2015, Kent and Fotios 2017, Osterhaus 2008, Rea 1982, Van Den Wymelenberg 2014). For instance, a survey

on the de Boer glare rating scale showed that the descriptor "Satisfactory" was most of the time misunderstood (Gellatly and Weintraub 1990). Another study showed a significant difference in interpretation between the perceived discomfort rating and the acceptance rating of glare (Geerdinck 2012). According to the results, a setting that is acceptable is not necessarily comfortable, suggesting that these two concepts should not be merged in a single scale such as in the De Boer scale.

- number of scale response points

Due to the abundance of existing glare rating scales, the amount of response points is not fixed. Rating scales can have three (Osterhaus and Bailey 1992), four (Fisekis et al. 2003), five (Tuaycharoen and Tregenza 2007), six , seven , eight (Shin et al. 2012), nine (Carlucci et al. 2015), ten (Stringham et al. 2011) or even more response points. The high variation in rating scale formats might have an influence on subject's assessment (Fotios 2015), as this issue has already been covered in the literature for other research fields (Garland 1991, Weijters et al. 2010).

- stimulus range bias

The stimulus range available to the subject has a significant influence on his or her evaluation (Kent and Fotios 2017). Depending on the stimulus range presented, a situation might be rated as comfortable in one experiment and uncomfortable in another one. This is due to the fact that subjects make relative evaluations, which should not be generalized as absolute evaluations. For instance, from several experiments on visual preferences, it was observed that the mean preferred illuminance always lies in the middle of the available range of illuminances (Fotios and Cheal 2010, Fotios et al. 2011, Logadóttir et al. 2011, Logadóttir et al. 2013). The effect of range bias on discomfort glare perception was first demonstrated by Lulla and Bennett (Lulla and Bennett 1981). This bias was then also reported by Geerdinck et al. as the potential cause to a discrepancy in the results of an experiment on discomfort glare perception (Geerdinck et al. 2014).

- anchor effect

The sequence in which glare situations are presented to the subject has a direct influence on his or her evaluation of discomfort glare (Kent and Fotios 2017). If glare situations are presented with an increasing discomfort and the first situation is overrated by the subject, every following situation tend to be over-rated as well. This is especially true in the case of a Hopkinson-like multiple-criterion adjustment method, as it has been recently demonstrated (Kent and Fotios 2017, Kent et al. 2017b). This anchor effect can be avoided by randomizing the sequence of stimuli presented to the subject.

- learning effect

The learning effect appears when the same subject is asked to do the same task several times. The more he/she will perform the task, the greater the learning effect will be as the subject will get bored and tried to complete the task as quickly as possible. Therefore, if several glare assessments from the same subject are needed, the learning effect can affect the subject's responses and cause bias in the results. This effect can be avoided by randomizing the stimuli, or at least verified by using a null condition (Fotios 2015).

- laboratory versus field experiment

When asking subjects about discomfort glare perception, it seems like they have a different tolerance towards discomfort glare whether the experiment takes place in a laboratory environment or in the field. It has indeed been acknowledged for road lighting that discomfort glare is assessed more critically in a laboratory test than in the field (Völker et al. 2017). DGP and DGI thresholds appear to be diverging as well between laboratory (Wienold 2009a) and field (Hirning et al. 2013) studies, although in this case, subjects seem to be less tolerant towards discomfort glare in the field.

For all these reasons, special attention should be paid when designing an experiment on discomfort glare involving subjects. Design recommendations, such as the use of a control situation with no discomfort glare or the sequence randomization, should be adopted (i.e. (CIE 2014)) to reduce the probability of bias in the results. Moreover, more research is required to study the influence of glare rating scales on discomfort glare perception. For instance, a comparative study on the performance of various glare rating scale formats would be very useful to suggest a universal glare rating scale, which should be adopted by CIE and used by all subsequent studies.

Table 4. Factors related to the glare experiment characteristics having a potential influence on discomfort glare perception from daylight. *Author(s)*/*Year* = authors having studied the factor, classified by chronological order; *Subjects* = number of subjects having participated in the study; *Evaluations* = number of glare evaluations made during the study; *Influence* = detection or not of an influence of the factor on discomfort glare perception in the study; *Influence direction* = direction of the influence of the factor (increase or decrease of discomfort glare perception) –should be used to evaluate the agreement rate between studies–; *Influence indicator* = likelihood of the influence of the factor on discomfort glare perception.

Factor	Author(s)	Year	Subjects	Evaluations	Influence	Influence direction	Influence indicator
Time of the day	Borisuit et al.	2015	25	400	X		
	Kent et al.	2015a/b	30	480	V	A	**SOMEWHAT LIKELY**
	Altomonte et al.	2016a/b	20	960	V	A	
	Kent et al.	2017	40	720	V	A	
Season	Van Den Wymelenberg	2012	93	1488	V	A	**SOMEWHAT LIKELY**
Task difficulty	Sivak et al.	1989	12	1080	V	A	**SOMEWHAT LIKELY**
	Flannagan et al.	1990	24	4320	V	A	
	Osterhaus & Bailey	1992	26	?	V	B	
	Altomonte et al.	2016a/b	20	960	V	A	
	Völker et al.	2017	R	R	V	?	
Glare rating scales and experimental design	Lulla & Bennett	1981	20	360	V	NA	**MORE LIKELY**
	Rea	1982	6	36	V	NA	
	Gellatly & Weintraub	1990	26	?	V	NA	
	Garland	1991	448	?	V	NA	
	Osterhaus	2008	P	P	V	NA	
	Weijters et al.	2010	1433	?	V	NA	
	Fotios et al.	2011	57	?	V	NA	
	Geerdinck	2012	42	840	V	NA	
	Geerdinck et al.	2014	42	668	V	NA	
	Van Den Wymelenberg	2014	R	R	V	NA	
	Fotios	2015	R	R	V	NA	
	Kent et al.	2017	22	264	V	NA	
	Kent & Fotios	2017	R	R	V	NA	
	Völker et al.	2017	R	R	V	NA	

R = literature review S = survey O = objective glare rating P = authors' point of view ? = information not available X = no influence of the factor V = influence of the factor

3.3. Related to the observer

3.3.1. General characteristics

3.3.1.1. Gender

The gender of a person as a factor influencing glare perception has already been examined in various studies (Iwata et al. 1992a, Kent et al. 2015c, Pulpitlova and Detkova 1993, Saur 1969, Shin et al. 2012, Sivak et al. 1989, Tuaycharoen and Tregenza 2007). They all came to the conclusion that the perception of discomfort glare is the same whether the subject is a man or a woman. A large survey on Indoor Environmental Quality has, however, suggested that women are more likely to complain about indoor comfort factors than men (Kim et al. 2013). It can still be assumed that gender does not influence the perception of discomfort glare.

3.3.1.2. Age

The subject's age is quite a controversial factor in the assessment of discomfort glare. As with a growing age, absolute sensitivity to light, contrast sensitivity and amount of light reaching the retina are reduced, several authors (Boyce 2014, Karwowski 2006, Mainster and Turner 2012, Narisada and Schreuder 2004) believe age should have an influence, even a small one, on our perception of discomfort glare. Bennett was the first to develop a short formula to assess the Borderline between Comfort and

Discomfort (BCD) level according to the subject's age, since a significant correlation was found between age and BCD level in one of his experiments (Bennett 1977):

$$BCD = \frac{80000}{Age\ (in\ years)}[cd/m^2] \quad (6)$$

Flannagan (Flannagan 1999) reinforced the hypothesis that older subjects give generally higher discomfort ratings than younger subjects in a study with artificial glare sources. Iwata and Tokura also noticed a difference between young and elderly subjects while developing the new position index (Iwata and Tokura 1997). Laboratory and field studies from Kuhn et al. on discomfort glare from daylighting have also suggested that the age effect exists but its statistical significance is very low (Kuhn et al. 2013). Völker et al. reinforced the hypothesis, suggesting that older people are less tolerant towards discomfort glare but that this difference is very small (Völker et al. 2017). On the opposite, a study from Wolska and Sawicki asserted that younger people were more sensitive to discomfort glare than older people (Wolska and Sawicki 2014). This was reinforced by a recent study on the glare effect, which observed that glare thresholds were higher for the "aged" group (Facchin et al. 2017).

But in several other studies, the age effect on perceived discomfort glare is refuted. Saur did not observe any effect of the subjects' age in his study on the physiological aspects of discomfort glare for car users (Saur 1969). No relation was either found between age and ratings in Vos and Van Bergem's study on subjective reactions to emitted light of greenhouses (Vos and Van Bergem-Jansen 1995). Furthermore, neither Osterhaus (Osterhaus 2001), Shin et al. (Shin et al. 2012) nor Hirning et al. (Hirning et al. 2014) found a statistically significant relationship between people's age and the level of glare experienced in their respective experiment or survey. Although in one experiment, older subjects self-reported as statistically more sensitive to brightness, the measured sensitivity to brightness, which was assessed by asking the subject to rate discomfort glare from artificial glare sources, did not reveal a significant difference between age groups neither (Van Den Wymelenberg 2012). Kent et al. studied the age effect as a personal factor influencing glare sensation (Kent et al. 2015a) but could not demonstrate any statistically significant influence of the age on individual glare sensation.

More recently, a study of Akashi et al. suggested that, compared to a group of younger subjects, there was a large deviation in glare sensitivity between older subjects (Akashi et al. 2017). They explained that this large deviation depended on the visual characteristics of the observers since these visual characteristics can cause the subject to be more sensitive to one of the two types of glare –absolute or relative.

From all these studies, it can be concluded that if there is an effect of age on discomfort glare perception, this effect might be weak, or even negligible, and depending more on the visual characteristics of the observer than on his or her age.

3.3.1.3. Culture

The culture of a subject is defined in this case as the climatic and indoor conditions to which the subject has been accustomed during the major part of his life, his behavior towards this indoor environment and his expectations about it. In consequence to this definition, people from North America would be treated as a different cultural group than people from Asia as they did not experience the same environment in the past. Several observations made in the last thirty years suggest that culture could be a factor influencing discomfort glare perception.

The first observation was made by Subova et al. while they were conducting a laboratory experiment on the subjective response to discomfort glare in Slovakia (Subova et al. 1991). From the results of their study, a difference in subjective discomfort glare levels was noticed between the Slovak subjects and the subjects of a similar study carried out in the USA (MacGowan et al. 1988). It was hypothesized that the difference "*might be caused by a greater sensitivity of the population in Middle Europe adapted to lower luminance conditions*". Iwata et al. made a similar assumption regarding the difference in tolerance towards discomfort glare between Japanese and British subjects (Iwata et al. 1992a). Japanese

subjects were reported in the study as being tolerant to higher levels of discomfort glare than British subjects from a study of Hopkinson (Hopkinson 1971, Petherbridge and Hopkinson 1950). This observation should, however, be tempered since the procedures between Hopkinson and Iwata et al.'s studies were not exactly the same. Pulpitlova and Detkova carried out another study in Slovakia based on Hopkinson's discomfort glare scale (Pulpitlova and Detkova 1993). The mean luminance values evaluated by the Slovakian subjects for each discomfort glare level were similar to those evaluated by American subjects (MacGowan and Emery 1986), but differed from the ones evaluated by Japanese subjects (Iwata et al. 1992a). Lee and Kim reinforced the assumption that Asians have a different tolerance towards discomfort glare compared to Caucasians (Lee and Kim 2007). The DGI thresholds proposed by Hopkinson and the ones obtained from their study with Asian subjects were compared, and indicated a significant difference suggesting that at high glare source luminance, Caucasians felt more discomfort glare than Asians. However, in Kent et al. study on factors influencing discomfort glare perception, the subject's ethnicity was not correlated with the individual glare perception (Kent et al. 2015a). This might be explained by the fact that even if the subjects in this study came from various ethnicities, they were all accustomed to the same climatic and environmental conditions as they lived in the same country. Therefore, this ethnicity effect cannot be incorporated in the culture effect as described earlier. Recently, Huang and Wang developed the DGI_{China} on the basis of the DGI to provide a discomfort glare index consistent with Chinese people's visual characteristics (Huang and Wang 2016). The thresholds of the DGI_{China} scale have been set higher than those of the usual DGI scale, which implies that Chinese people might tolerate higher discomfort glare than Hopkinson's study subjects. Similarly, a field study conducted in Indonesia (Mangkuto et al. 2017) evaluated new thresholds for the DGP index, which are much lower than the original thresholds developed by Wienold et al. for European populations (Wienold and Christoffersen 2006). This last observation might, however, be related to the difference in tolerance towards discomfort glare between laboratory and field studies, as mentioned above. A study by Ko and Choi also investigated the difference in UGR glare thresholds between Caucasian and Korean subjects (Ko and Choi 2017). A modified version of the Unified Glare Rating (UGR) index was developed since it was observed that Korean subjects tolerated higher levels of discomfort glare than Caucasian subjects. At last, a field experiment was conducted by Pierson and others (Pierson et al. 2017) in Belgium and in Chile to compare discomfort glare perception in these two countries. From the results, it was hypothesized that current glare indices might not be relevant for every cultural background, since Chileans appear to perceive discomfort glare differently than Belgians.

These studies imply that culture, as defined in this paper, could have an influence on discomfort glare perception. Until now, discomfort glare indices have been developed through experiments involving particular populations: i.e. British subjects for DGI (Hopkinson 1971), Japanese subjects for PGSV (Tokura et al. 1996), German and Danish subjects for DGP (Wienold and Christoffersen 2006). No study has examined that these indices could be used analogously for subjects having different cultures, namely subjects experiencing different climates and having different sensitivities towards daylight. Since the observer's culture might influence his or her discomfort glare perception, a deeper understanding of the effect of culture is required.

3.3.1.4. Chronotype

The chronotype of a person is the behavioral manifestation of his or her circadian rhythm which is regulated by daylight. The behavioral manifestation of the circadian rhythm means our propensity to fall asleep at a certain time during the 24-hours loop. An early chronotype person will therefore fall asleep early in the evening and wake up early in the morning.

As tolerance to glare source luminance became smaller with the progression of subjects' chronotype from early to late type, Kent et al. concluded that earlier chronotype subjects, namely the subjects waking up early in the morning, tolerate higher levels of discomfort glare (Kent et al. 2015a, Kent et al. 2015c). But as mentioned before, and despite the promising results of Kent et al.'s experiment, more than one significant correlation is needed to acknowledge the influence of chronotype on discomfort glare perception.

3.3.1.5. Self-assessed glare sensitivity

The glare sensitivity is a characteristic that subjects could potentially determine for themselves. By asking ourself whether we often wear sunglasses in sunny weather can help us figure it out. The self-assessed glare sensitivity, or the self-reported sensitivity to brightness, was already compared to the measured sensitivity to brightness (Van Den Wymelenberg 2012). Although the correlation between the self-assessed and measured sensitivity to brightness was rather low, it seemed to hold at the extreme. This means that the subjects could not judge on a multiple-points scale their level of sensitivity but could classify themselves into the sensitive or non-sensitive categories.

First in 1969, Saur demonstrated that self-assessed glare sensitive subjects have a decreased tolerance of discomfort glare (Saur 1969). This assumption was confirmed in a survey for which a growing relationship between the average glare experienced and the perceived sensitivity to glare was observed (Osterhaus 2001). The self-assessed glare sensitivity was also studied as one of the criteria in window-blind control models as it was assumed that this factor could partly explain the wide variability between subjects' discomfort glare perception (Inkarojrit 2005). However, from the field study, no statistically significant correlation could be observed between the self-reported glare sensitivity and discomfort glare perception. More recently, Rodriguez and Pattini (Rodriguez and Pattini 2014) observed that when the glare source lies in the central vision, glare-sensitive people perceived higher discomfort glare than the others. However, this observation could not be confirmed in a second experiment (Rodriguez et al. 2016). A study from Kent et al. reinforced the assumption that self-assessed glare sensitivity is not a factor influencing discomfort glare perception (Kent et al. 2015a, Kent et al. 2015c).

The influence of the self-assessed glare sensitivity on discomfort glare perception is not clear as recent studies tend to reject the effect. More research is needed to determine if the subjective evaluation that a person makes of his or her own sensitivity to glare has an impact on his or her perception of a discomfort glare stimulus.

Table 5. Factors related to the observer's general characteristics having a potential influence on discomfort glare perception from daylight. *Author(s)/Year* = authors having studied the factor, classified by chronological order; *Subjects* = number of subjects having participated in the study; *Evaluations* = number of glare evaluations made during the study; *Influence* = detection or not of an influence of the factor on discomfort glare perception in the study; *Influence direction* = direction of the influence of the factor (increase or decrease of discomfort glare perception) –should be used to evaluate the agreement rate between studies–; *Influence indicator* = likelihood of the influence of the factor on discomfort glare perception.

Factor	Author(s)	Year	Subjects	Evaluations	Influence	Influence direction	Influence indicator
Gender	Saur	1969	35	70	X		**ALMOST CERTAINLY NULL**
	Sivak et al.	1989	12	1080	X		
	Iwata et al.	1992a	40	480	X		
	Pulpitlova & Detkova	1993	57	456	X		
	Tuaycharoen & Tregenza	2007	168	600	X		
	Shin et al.	2012	48	2400	X		
	Kim et al.	2013	38257	S	X		
	Kent et al.	2015a/c	30	480	X		
Age	Saur	1969	35	70	X		**INCONCLUSIVE**
	Bennett	1977	199	1393	V	A	
	Vos & Van Bergem-Jansen	1995	400	S	X		
	Iwata & Tokura	1997	71	2130	V	A	
	Flannagan	1999	12	288	V	A	
	Osterhaus	2001	83	S	X		
	Shin et al.	2012	48	2400	X		
	Van Den Wymelenberg	2012	93	1488	X		
	Hirning et al.	2013a	468	493	X		
	Kuhn et al.	2013	45	270	V	A	
	Wolska & Sawicki	2014	50	100	V	B	
	Kent et al.	2015a/c	30	480	X		
	Akashi et al.	2017	24	192	V	A/B	
	Facchin et al.	2017	50	4950	V	B	
	Völker et al.	2017	R	R	V	A	
Culture	Subova et al.	1991	32	256	V	?	**SOMEWHAT LIKELY**
	+ MacGowan et al.	1988	?	?			
	Iwata et al.	1992a	40	480	V	A	
	+ Petherbridge & Hopkins	1950	6	?			
	+ Hopkinson	1971	?	?			
	Pulpitlova & Detkova	1993	57	456	V	A	
	+ MacGowan & Emery	1986	?	?			
	+ Iwata et al.	1992a	40	480			
	Lee & Kim	2007	42	630	V	A	
	+ Hopkinson	1971	?	?			
	Kent et al.	2015a/c	30	480	X		
	Huang & Wang	2016	R	R	V	A	
	Ko & Choi	2017	176	1760	V	A	
	Mangkuto et al.	2017	86	86	V	?	
	+ Wienold & Christoffers	2006	76	349			
Chronotype	Kent et al.	2015a/c	30	480	V	A	**SOMEWHAT LIKELY**
Self-assessed glare sensitivity	Saur	1969	35	70	V	A	**INCONCLUSIVE**
	Osterhaus	2001	83	S	V	A	
	Inkarojrit	2005	25	83	X		
	Rodriguez & Pattini	2014	25	200	V	A	
	Kent et al.	2015a/c	30	480	X		
	Rodriguez et al.	2015	32	64	X		

R = literature review S = survey O = objective glare rating P = authors' point of view ? = information not available X = no influence of the factor V = influence of the factor

3.3.2. Vision characteristics

3.3.2.1. Optical correction

The optical correction factor expresses whether a person wears glasses, contact lenses or nothing. The wearing of glasses or lenses could influence discomfort glare perception as a modification is brought to the eyes of the subject.

First, in a study on physiological aspects of discomfort glare, no relationship was found between the perceived discomfort glare of a subject and its vision correction level (Saur 1969). In their work on discomfort glare from large sources, Iwata et al. did not detect any significant difference between subjects wearing glasses or lenses and those who did not (Iwata et al. 1992a, Iwata and Tokura 1997). Although Sivak et al. could show a tendency for subjects with optical correction to report more glare than subjects without correction, this difference in discomfort glare perception in road lighting was not statistically significant (Sivak et al. 1997). No difference in discomfort glare perception between subjects wearing glasses and subjects without could be found in other studies (Shin et al. 2012, Tuaycharoen and Tregenza 2007). More recently, Hirning et al. investigated this effect amongst others in a large survey and observed no statistically significant influence on perceived discomfort glare (Hirning et al. 2014), which confirms the assumption that the wearing of glasses or lenses does not affect the glare sensation.

3.3.2.2. Iris pigmentation

Iris pigmentation is the characteristic giving the eye its color. A popular belief is to think that according to their eye color, namely the iris pigmentation, people perceive glare differently. This belief seems to be based on unfounded assumptions since the iris pigmentation does not play any role in the mechanism of vision, and therefore probably not in the glare one either.

Nonetheless, some studies have examined the influence that iris pigmentation could have on perception of discomfort glare. In a study on discomfort glare for road safety, no correlation could be found between the eye color and the luminance level at which subjects feel discomfort glare (Saur 1969). Contrariwise, in a survey conducted by Osterhaus, a slight indication suggested that "*workers with lighter eye colors might, on average, perceive to be slightly more sensitive to glare and might be experiencing slightly higher levels of glare*" (Osterhaus 2001). But this information was not verified against lighting measurements, and it could as well be linked to the fact that subjects with light eyes are biased by the popular belief as they consider themselves as more sensitive to glare. Another similar trend of iris pigmentation influencing glare perception was reported in an experiment with an artificial glare source, as subjects with dark eyes reported lower discomfort glare perception (Bennett 1977). However, the effect was later refuted in an experiment to determine the effect of retinal pigment on visual discomfort (Stringham et al. 2011). It was concluded from the last that the iris pigmentation has no statistically significant influence on the perceived visual discomfort despite a visible trend. Recently, Rodriguez et al. (Rodriguez et al. 2016) noticed that more light-eyed volunteers were found in the glare-sensitive group than in the glare-insensitive group in one of their experiments. But no statistically significant difference in discomfort glare perception could be found in the study between glare-sensitive and glare-insensitive subjects.

Despite tendencies indicating that light-eyed people could be more sensitive to discomfort glare, there is so far no statistically significant evidence that iris pigmentation influence discomfort glare perception. Additional experiments focused on this particular matter should be conducted to confirm or infirm this hypothesis.

3.3.2.3. Macular pigment optical density

The macular pigment optical density (MPOD) is the level of density of protective pigment in the macula. The macula is a small area located in the retina where cones, which are the photoreceptors mainly responsible for the photopic vision, have the highest density. The yellow macular pigments are derived from carotenoids and deposited in this photoreceptor axon layer. A high MPOD level protects the retina as the macular pigments absorb high-energy short-wavelength light.

The effect of MPOD on visual discomfort, and specifically on discomfort glare, has been studied several times. From a study on the relationship between individuals' discomfort glare thresholds and spatial distribution of macular pigments (MP) in the retina (Stringham et al. 2004), it was assumed that MP acted as a spatially integrated filter against short-wavelength light and that a person with a relatively high MP level perceived less discomfort glare in the central viewing. Another experiment from Stringham et al. showed that subjects with broader MPOD spatial distribution would perceive less discomfort glare (Stringham et al. 2011). They made therefore the hypothesis that subjects having relatively high MP levels would tolerate more intense lights. The assumption that macular pigments reduce discomfort glare by absorbing short-wavelength light was endorsed by Lien and Hammond (Lien and Hammond 2011). However, Loughman et al. conducted another experiment on the role of MPOD, and concluded that visual performance under glare conditions was not related to MPOD (Loughman et al. 2010).

No definitive conclusion can be drawn from these studies on the effect of MPOD on discomfort glare perception, as the MPOD mechanism towards discomfort glare is not well understood.

3.3.2.4. Cortical hyperexcitability

The cortical hyperexcitability is the degree of activity of the neurons in the visual cortex, namely the neural tissues composing the outer layer of the part of the brain responsible for vision. The neurons actually mediate communications of the nervous system by propagating electrical signals generated by their excitable membrane.

A study has shown that the cortical hyperexcitability of a person, meaning the degree to which his or her neuronal activity can arise, influences his or her sensitivity to discomfort glare (Bargary et al. 2015). The authors observed that the glare-sensitive subjects showed significantly greater activity in the visual cortex. Moreover, the data suggested a positive correlation between the magnitude of the neuronal response and individual's sensitivity to discomfort glare.

This neuronal effect on discomfort glare perception could explain the difference existing between glare-sensitive and glare-insensitive person. These two factors, namely the neuronal effect and the self-assessed glare sensitivity, might therefore overlap. Only one of them should be taken into account as a new variable of discomfort glare models. The self-assessed glare-sensitivity, despite its lack of accuracy, might be easier to implement than the cortical hyperexcitability.

3.3.2.5. Contrast sensitivity

With the ability to resolve fine details, namely the visual acuity, contrast sensitivity is the other important visual characteristic that refers to the ability of the eye to detect a difference in luminance between an object and its background (Karwowski 2006). Contrast sensitivity depends on the spatial frequency, namely the frequency of the contrast pattern in the field of view, and the level of contrast.

Several studies have investigated the relationship between contrast sensitivity and disability glare as people often have a loss in contrast sensitivity when there is light scattering in the eyes (Arranz et al. 2014, Bach et al. 2008, Bühren et al. 2006, Paulsson and Sjostrand 1980, Siah et al. 2017). Similarly, contrast sensitivity could have an influence on discomfort glare perception. As the contrast sensitivity curve of the human visual system peaks at a particular frequency and drops on either side of that peak frequency (Hilz and Cavonius 1974), the discomfort glare perception was observed to behave exactly inversely (Eble-Hankins 2008). From subjects' evaluations of discomfort glare, discomfort is minimized at the spatial frequency where contrast sensitivity peaks, and increases on either side of that minimum frequency. Contrast sensitivity could thus be an interesting variable to study as it could improve our knowledge of the mechanism of discomfort glare.

Table 6. Factors related to the observer's vision characteristics having a potential influence on discomfort glare perception from daylight. *Author(s)/Year* = authors having studied the factor, classified by chronological order; *Subjects* = number of subjects having participated in the study; *Evaluations* = number of glare evaluations made during the study; *Influence* = detection or not of an influence of the factor on discomfort glare perception in the study; *Influence direction* = direction of the influence of the factor (increase or decrease of discomfort glare perception) –should be used to evaluate the agreement rate between studies–; *Influence indicator* = likelihood of the influence of the factor on discomfort glare perception.

Factor	Author(s)	Year	Subjects	Evaluations	Influence	Influence direction	Influence indicator
Optical correction	Saur	1969	35	70	X		**ALMOST CERTAINLY NULL**
	Iwata et al.	1992a	40	480	X		
	Iwata & Tokura	1997	71	2130	X		
	Sivak et al.	1997	16	1600	X		
	Tuaycharoen & Tregenza	2007	168	600	X		
	Shin et al.	2012	48	2400	X		
	Hirning et al.	2013a	468	493	X		
Iris pigmentation	Saur	1969	35	70	X		**INCONCLUSIVE**
	Bennett	1977	199	1393	V	A	
	Osterhaus	2001	83	S	V	A	
	Stringham et al.	2011	26	468	X		
	Rodriguez et al.	2015	32	64	X		
Macular pigment optical density	Stringham et al.	2004	4	O	V	A	**SOMEWHAT LIKELY**
	Loughman et al.	2010	142	O	X		
	Lien & Hammond	2011	R	R	V	A	
	Stringham et al.	2011	26	468	V	A	
Cortical hyperexcitability	Bargary et al.	2015	28	280 + O	V	A	**SOMEWHAT LIKELY**
Contrast sensitivity	Eble-Hankins	2008	67	1608	V	A	**SOMEWHAT LIKELY**

R = literature review S = survey O = objective glare rating P = authors' point of view ? = information not available X = no influence of the factor V = influence of the factor

3.3.3. Present state

3.3.3.1. Previous luminous environment

The previous luminous environment stands for the lighting conditions that a subject experienced during the period preceding the assessment of glare, whether it is the previous hours, day, week or even longer.

A first statistically significant correlation was found between one's occupation environment type, namely whether a person works inside or outside, and the BCD level (Bennett 1977). Bennett observed that subjects experiencing a lot of daylight at work, and therefore during the days preceding the glare evaluation, have a higher tolerance towards discomfort glare. Similarly, another laboratory experiment suggested that whether a subject had spent the last day in a shadowed or overlit environment, his or her discomfort glare thresholds were significantly different (Pulpitlova and Detkova 1993). Kent et al. also observed in their experiment that subjects having experienced daylight in the morning tolerated slightly higher degree of discomfort glare but this effect could not be demonstrated as statistically significant (Kent et al. 2015a, Kent et al. 2015c). A direct trend between discomfort glare perception and prior light exposure was deduced from a similar experiment, especially on glare evaluations made in the evening (Altomonte et al. 2016a, 2016b).

No strongly significant evidence towards higher tolerance of discomfort glare for people having previously experienced daylight could be presented, although a tendency was observed. Additional research is needed to determine whether this effect is real and whether short-term, post-awake, previous days, or previous weeks sunlight availability is more influent on discomfort glare perception.

3.3.3.2. Physical state

Since physical conditions such as diseases, head pain, back pain, etc., can reduce the perceived comfort, these could impact the visual comfort of a subject and influence his or her discomfort glare perception in a negative way.

When asking subjects about their current physical state in a survey on discomfort glare sensitivity, no influence could be found of the physical state on discomfort glare perception (Osterhaus 2001). However, only one survey investigated this factor and the subjective results were not compared to measures of the lighting environment or glare indices. More research is therefore required to confirm that the way a person feels physically does not influence his or her perception of glare.

3.3.3.3. Emotional state

The current emotional state of a subject could affect his or her perception of discomfort glare in the sense that positive emotions such as joy, serenity, pride or amusement could lead the subject to be less critical of the luminous conditions. The opposite could be true for negative emotions.

Similarly to the physical state, when asking subjects about their current emotional state and their sensitivity to discomfort glare, no correlation could be found with frequency of discomfort glare perception (Osterhaus 2001). However, a small influence was observed in another study establishing that, surprisingly, subjects in a better mood would experience slightly higher discomfort from glare (Altomonte et al. 2016a, 2016b). More research is needed to ascertain the assumption that subject's emotional state has an influence on discomfort glare perception.

3.3.3.4. Caffeine ingestion

When associated with bright light exposure, caffeine ingestion has an effect on melatonin secretion and therefore on the circadian rhythm (Wright et al. 1997). Caffeine ingestion could also have an influence on discomfort glare perception.

Two studies investigated the temporal factors influencing discomfort glare perception, amongst which the caffeine ingestion (Altomonte et al. 2016a, 2016b, Kent et al. 2015a, Kent et al. 2015c). According to the statistical analyses, there is a tendency for the subjects not having ingested caffeine to report discomfort glare at higher levels of glare source luminance. More results going in this direction are requested to confirm this hypothesis.

3.3.3.5. Food ingestion

Since circadian rhythms can be entrained by time-dependent schedules of light exposure, caffeine, and food intake (Kent 2016), the food ingestion prior to the glare evaluation has also been studied for its influence on discomfort glare perception. No statistically significant influence could be found in Kent et al.'s study (Kent et al. 2015a, Kent et al. 2015c). A significant difference was observed in another study between subjects having ingested food or not, although this difference was below the threshold of practical relevance (Altomonte et al. 2016a, 2016b).

The influence that food ingestion could have on discomfort glare perception is not evident, and further experiments should be conducted to dismiss or endorse this factor.

3.3.3.6. Fatigue

Fatigue could influence discomfort glare perception as tired subjects could be less tolerant towards discomfort glare in their field of view (Kent 2016).

From two laboratory experiments, some fatigue effects of small but relevant size were detected, such as a higher tolerance to luminance levels for less tired subjects (Altomonte et al. 2016a, 2016b, Kent et al. 2015a, Kent et al. 2015c, Kent 2016). These small fatigue effects do not allow, however, to draw conclusions on the influence of subjects perceived levels of fatigue on the discomfort glare sensation. Moreover, it is well likely that fatigue and time of the day are dependent factors. Attention should thus be paid to these factors so that they do not overlap each other.

Table 7. Factors related to the observer's present state having a potential influence on discomfort glare perception from daylight. *Author(s)/Year* = authors having studied the factor, classified by chronological order; *Subjects* = number of subjects having participated in the study; *Evaluations* = number of glare evaluations made during the study; *Influence* = detection or not of an influence of the factor on discomfort glare perception in the study; *Influence direction* = direction of the influence of the factor (increase or decrease of discomfort glare perception) –should be used to evaluate the agreement rate between studies–; *Influence indicator* = likelihood of the influence of the factor on discomfort glare perception.

Factor	Author(s)	Year	Subjects	Evaluations	Influence	Influence direction	Influence indicator
Previous luminous environment	Bennett	1977	199	1393	V	A	**INCONCLUSIVE**
	Pulpitlova & Detkova	1993	57	456	V	?	
	Kent et al.	2015a/c	30	480	X		
	Altomonte et al.	2016a/b	20	960	V	B	
Physical state	Osterhaus	2001	83	S	X		**SOMEWHAT UNLIKELY**
Emotional state	Osterhaus	2001	83	S	X		**INCONCLUSIVE**
	Altomonte et al.	2016a/b	20	960	V	A	
Caffeine ingestion	Kent et al.	2015a/c	30	480	V	A	**SOMEWHAT LIKELY**
	Altomonte et al.	2016a/b	20	960	V	A	
Food ingestion	Kent et al.	2015a/c	30	480	X		**SOMEWHAT UNLIKELY**
	Altomonte et al.	2016a/b	20	960	X		
Fatigue	Kent et al.	2015a/c	30	480	V	A	**SOMEWHAT LIKELY**
	Altomonte et al.	2016a/b	20	960	V	A	

R = literature review S = survey O = objective glare rating P = authors' point of view ? = information not available X = no influence of the factor V = influence of the factor

4. Conclusion

Factors potentially influencing discomfort glare perception from daylight are listed and reviewed. This literature study categorizes the influence of these factors on discomfort glare perception by introducing an influence indicator based on the amount of studies, the sample size of these studies, and the agreement between them. The suggested categories rate a factor influence as "almost certain", "more likely", "somewhat likely", "inconclusive", "somewhat unlikely", "less likely", or "almost certainly null". The magnitude of the influence of each factor can, however, not be determined from the data available in the literature.

From Tables 1 to 7, it can be observed that some factors – the gender of the observer and the optical correction – have almost certainly no influence on discomfort glare perception. Others – the food ingestion and the physical state of the observer – should not have any influence, even though additional studies are required to confirm it. On the other hand, it can be seen as well that a large number of factors are expected to be influencing discomfort glare perception. Amongst these factors, some – the saturation effect, the spectrum and color temperature of light– would just need one or two large studies to validate their influence, while others – the time of the day, the task difficulty, the culture, the chronotype, the MPOD, the cortical hyperexcitability, the contrast sensitivity, the season, the caffeine ingestion, and the fatigue – still need considerable investigation before drawing any conclusion on their influence on discomfort glare perception. The glare rating scales and experimental design factor includes several subfactors, which explains the non-applicability of the *Influence direction* information in Table 4. This considerable factor is also believed to influence discomfort glare perception, but several studies are still required to assert the influence of all subfactors. Moreover, the literature existing on several factors – the view direction and position of the observer, the attractiveness of the view through the window, the room temperature, the age, the self-assessed glare sensitivity, the iris pigmentation, the previous luminous environment, and the emotional state of the observer – was inconclusive about their influence on discomfort glare perception. As it can be recognized in the tables, the uncertainty is due to the fact that the studies having investigated these factors are either not agreeing on an influence of the factor or on the effect of this influence on discomfort glare perception. Also, precaution should be taken as some factors might interact. For instance, fatigue and time of the day are two factors closely linked. Therefore, the correlation found between fatigue and perceived discomfort glare should not be directly related to the influence of fatigue since the time of the day could also have played a role. The self-assessed glare sensitivity and the cortical hyperexcitability also seem to be related. For that reason, more research is necessary to clarify the influence of these factors. At last, factors having an almost certain influence in the mechanism of discomfort glare are, as expected, the luminance of the glare source, the adaptation level, the contrast effect, the size and the position of the glare source as seen by the observer.

From this work, it can be generally concluded that more work is needed to explain the high variability existing between individuals' discomfort glare perception, since there are a lot of factors potentially influencing discomfort glare perception. This literature review helps defining which factors have to be deeper investigated and to what extent. As a result, discomfort glare models might be adapted in the future according to the newly found influencing factors. Although it is recommended that each

researcher defines his or her own prioritization list of factors requiring more investigation, some recommendations can be drawn from the tables and the influence indicator.

First efforts should be directed towards factors classified as more or less likely. For instance, a large experiment should be conducted on the perception of discomfort glare from filtered daylight to confirm the influence of the spectrum of light on discomfort glare perception. This will be very useful as new glazing types, such as electrochromic windows, are currently being developed. Another study should focus on validating the proposition that discomfort glare can be due to two main effects, the saturation and the contrast glare, so that both effects are included in discomfort glare models in the future. Last but not least, studies on the influence of glare rating scale and experimental design on the collection of subjective perceptions are greatly needed. This will ensure that the knowledge that is being built in the field of visual discomfort is not based on biased results. Then, factors of which the influence is classified as somewhat likely or unlikely should be further investigated. The influence probability of these is usually based on a small number of studies proving or denying the effect, or one study presenting opposite results questions the overall trend. Therefore, these factors require larger studies and stronger evidence to support or reject their influence on discomfort glare perception. Lastly, factors having an inconclusive influence should be looked at. These are generally controversial factors as different studies results do not agree. This suggests that either the influence of these factors is very small and maybe not significant, or the method used to study the factor is not always adequate. As an example, the attractiveness of the view through the window was believed to considerably influence discomfort glare perception due to the results of several laboratory experiments mainly using simulated windows. However, recent field studies have been challenging this assumption as this effect could not be observed from the results with real window views. It was therefore concluded that when the view implies no strong attraction or revulsion, its influence on discomfort glare perception is somehow largely reduced.

Nonetheless, the fact that physiological and psychological factors might influence discomfort glare perception brings a different perspective on discomfort glare indices. Glare in the field of view actually produces a sensation to the observer, who perceives it as more or less discomforting according to several psychological factors and some of his or her own physiological characteristics. The reason why the term ‘discomfort glare perception’ was used instead of ‘discomfort glare’ is due to the authors’ interest in the visual discomfort as perceived by the observer. Strong and statistically significant correlations could therefore be found between discomfort glare perception and physiological and psychological factors like the MPOD or the emotional state of the observer. As subjective perception matters in the case of discomfort glare, indices should not be made exclusively of physical quantities. Moreover, as it has already been suggested in 1950 (Petherbridge and Hopkinson 1950), a discomfort glare index should not rate on a numerical scale an assessment of a subjective effect, as it will naturally be interpreted arithmetically. A “percentage of people who would be disturbed” could be a more appropriate and better interpreted method to rank a certain discomfort glare stimulus.

No exact correlation should be expected between discomfort glare assessed by an index and perceived by a subject though. There are two reasons for this:

- on the one hand, because, besides the here listed psychological or physiological factors, some unknown others could be involved in the discomfort feeling. That is the reason why there is such a large spread amongst people when assessing discomfort due to glare;
- on the other hand, because the intensity of influence and interaction of the factors involved in the glare process cannot be precisely understood and explained, hence the uncertainty of existing discomfort glare models based on statistics.

However, a close approach of the perceived discomfort glare could be obtained by controlling, or at least monitoring, as many factors as possible. The set up and the questionnaire of an experiment aiming to collect subjective assessments of discomfort glare is thus of major importance.

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References

Akashi Y, Asano S, Kakuta Y, Fujita T. 2013. Visual mechanisms of discomfort glare sensation caused by leds. CIE Centenary Conference. Paris, France. April 12-19, 2013.

Akashi Y, Kojima S, Aoki T, Inatani M. 2017. Ageing effects on discomfort glare sensation and their mechanisms. CIE 2017 Midterm Meeting. Jeju, South Korea. October 21-28, 2017.

Altomonte S, Kent MG, Tregenza PR, Wilson R. 2016a. Task difficulty, temporal variables and glare response. PLEA 2016. Los Angeles, USA. July 11-13, 2016.

Altomonte S, Kent MG, Tregenza PR, Wilson R. 2016b. Visual task difficulty and temporal influences in glare response. Building and Environment. 95:209-226. doi:10.1016/j.buildenv.2015.09.021.

Aries MBC, Veitch JA, Newsham GR. 2010. Windows, view, and office characteristics predict physical and psychological discomfort. Journal of Environmental Psychology. 30(4):533-541. doi:10.1016/j.jenvp.2009.12.004.

Arranz I, Matesanz BM, Issolio L, Menendez JA, Mar S, Aparicio JA. 2014. Light adaptation in letter contrast sensitivity: The influence of optical and neural mechanisms. Lighting Research & Technology. 46:476–488. doi:10.1177/1477153513484633.

Bach M, Wesemann W, Kolling G, Buhren J, Krastel H, Schiefer U. 2008. Photopic contrast sensitivity. Local contrast perception. Ophthalmologe. 105(1):46-48, 50-49. doi:10.1007/s00347-007-1605-y.

Bargary G, Furlan M, Raynham PJ, Barbur JL, Smith AT. 2015. Cortical hyperexcitability and sensitivity to discomfort glare. Neuropsychologia. 69:194-200. doi:10.1016/j.neuropsychologia.2015.02.006.

Bellia L, Cesarano A, Iuliano GF, Spada G. 2008. Daylight glare: A review of discomfort indexes. Visual quality and energy efficiency in indoor lighting: today for tomorrow, international workshop. Rome, Italy. March 31-April 02, 2008.

Bennett CA. 1977. The demographic variables of discomfort glare. Lighting Design and Application. 7:22-24.

Berman SM, Bullimore MA, Bailey IL, Jacobs RJ. 1995. The influence of spectral composition on discomfort glare for large-size sources. The 1995 IESNA Annual Conference. New York, USA. July 30-August 02, 1995. doi:10.1080/00994480.1996.10748131.

Borisuit A, Linhart F, Scartezzini JL, Münch M. 2015. Effects of realistic office daylighting and electric lighting conditions on visual comfort, alertness and mood. Lighting Research & Technology. 47(2):192-209. doi:10.1177/1477153514531518.

Boubekri M, Boyer LL. 1992. Effect of window size and sunlight presence on glare. Lighting Research & Technology. 24(2):69-74. doi:10.1177/096032719202400203.

Bourassa CM, Wirtschafter JD. 1966. Mechanism of binocular increase of discomfort to high luminance. Nature. 212:1503–1504.

Boyce PR. 2014. Human factors in lighting - third edition. Boca Raton, USA: Taylor & Francis Group. 690p.

Bühren J, Terzi E, Bach M, Wesemann W, Kohnen T. 2006. Measuring contrast sensitivity under different lighting conditions: Comparison of three tests. Optometry & Vision Science. 83(5):290–298. doi:1040-5488/06/8305-0290/0.

Bullough JD. 2009. Spectral sensitivity for extrafoveal discomfort glare. Journal of Modern Optics. 56(13):1518-1522. doi:10.1080/09500340903045710.

Bülow-Hübe H. 2008. Daylight in glazed office buildings - a comparative study of daylight availability, luminance and illuminance distribution for an office room with three different glass areas. Lund, Sweden: Lund University. No. EBD-R--08/17. 98p.

Cai H, Chung T. 2012. Evaluating discomfort glare from non-uniform electric light sources. Lighting Research & Technology. 45(3):267-294. doi:10.1177/1477153512453274.

Cantin F, Dubois M-C. 2011. Daylighting metrics based on illuminance, distribution, glare and directivity. Lighting Research & Technology. 43(3):291–307. doi:10.1177/1477153510393319.

Carlucci S, Causone F, De Rosa F, Pagliano L. 2015. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. Renewable and Sustainable Energy Reviews. 47:1016-1033. doi:10.1016/j.rser.2015.03.062.

CEN. 2011. Light and lighting - basic terms and criteria for specifying lighting requirements. Brussels, Belgium: Comité Européen de Normalisation. No. EN 12665:2011. 55p.

Chaiwiwatworakul P, Chirarattananon S, Rakkwamsuk P. 2009. Application of automated blind for daylighting in tropical region. Energy Conversion and Management. 50(12):2927-2943. doi:10.1016/j.enconman.2009.07.008.

Chan Y-C, Tzempelikos A. 2013. Efficient venetian blind control strategies considering daylight utilization and glare protection. Solar Energy. 98(Part C):241-254. doi:10.1016/j.solener.2013.10.005.

Chauvel P, Collins JB, Dogniaux R, Longmore J. 1982. Glare from windows: Current views of the problem. Lighting Research & Technology. 14(1):31-46. doi:10.1177/096032718201400103.

Chen P-L, Liao C-H, Li H-C, Jou S-J, Chen H-T, Lin Y-H, Tang Y-H, Peng W-J, Kuo H-J, Sun P-L et al. 2015. A portable inspection system to estimate direct glare of various led modules. International Conference on Optical and Photonic Engineering. Singapore, Singapore. April 14-16, 2015. doi:10.1117/12.2189599.

Christoffersen J, Johnsen K, Petersen E, Valbjorn O, Hygge S. 2000. Windows and daylight - a post-occupancy evaluation of danish offices. Lighting 2000. York, UK. July 09-11, 2000.

CIE. 1983. Discomfort glare in the interior working environment. Vienna, Austria: Commission Internationale de l'Eclairage. No. 55:1983. 52p.

CIE. 1995. Discomfort glare in interior lighting. Vienna, Austria: Commission Internationale de l'Eclairage. No. 117:1995. 41p.

CIE. 2014. Guidance towards best practice in psychophysical procedures used when measuring relative spatial brightness. Vienna, Austria: Commission Internationale de l'Eclairage. No. 212:2014. 65p.

Clear RD. 2013. Discomfort glare: What do we actually know? Lighting Research & Technology. 45(2):141-158. doi:10.1177/1477153512444527.

De Boer JB. 1967. Public lighting. London, UK: Cleaver-Hume. 693p.

Donners MAH, Vissenberg MCJM, Geerdinck LM, van den Broek-Cools JHF, Buddemeijer-Lock A. 2016. A psychophysical model of discomfort glare in both outdoor and indoor applications. CIE 2016 “Lighting Quality and Energy Efficiency”. Melbourne, Australia. March 3–5, 2016.

Dubois M-C. 2001. Impact of shading devices on daylight quality in offices - simulations with radiance. Lund, Sweden: Lund University. No. TABK--01/3062. 162p.

Eble-Hankins ML. 2008. Subjective impression of discomfort glare from sources of non-uniform luminance [PhD dissertation]. [Lincoln, USA]: University of Nebraska (UNL). 385p.

Eble-Hankins ML, Waters CE. 2005. Vcp and ugr glare evaluation systems: A look back and a way forward. The Journal of the Illuminating Engineering Society. 1(2):7-38. doi:10.1582/leukos.2004.01.02.001.

Eble-Hankins ML, Waters CE. 2009. Subjective impression of discomfort glare from sources of non-uniform luminance. The Journal of the Illuminating Engineering Society. 6(1):51-77. doi:10.1582/LEUKOS.2009.06.01003.

Einhorn HD. 1969. A new method for the assessment of discomfort glare. Lighting Research & Technology. 1(4):235-247. doi:10.1177/14771535690010040201.
Einhorn HD. 1979. Discomfort glare: A formula to bridge differences. Lighting Research & Technology. 11(2):90-94. doi:10.1177/14771535790110020401.
Facchin A, Daini R, Zavagno D. 2017. The glare effect test and the impact of age on luminosity thresholds. Frontiers in Psychology. 8:1132. doi:10.3389/fpsyg.2017.01132.
Fekete J, Sik-Lanyi C, Schanda J. 2009. Spectral discomfort glare sensitivity investigations. Ophthalmic and Physiological Optics. 29:1-6. doi:10.1111/j.1475-1313.2009.00696.x.
Fisekis K, Davies M, Kolokotroni M, Langford P. 2003. Prediction of discomfort glare from windows. Lighting Research & Technology. 35(4):360-371. doi:10.1191/1365782803li095oa.
Flannagan MJ. 1999. Subjective and objective aspects of headlamp glare: Effects of size and spectral power distribution. Ann Arbor, USA: University of Michigan. No. UMTRI-99-36. 19p.
Flannagan MJ, Weintraub DJ, Sivak M. 1990. Context effects on discomfort glare : Task and stimulus factors. Ann Arbor, USA: University of Michigan. No. UMTRI-90-35. 30p.
Fotios S. 2015. Research note: Uncertainty in subjective evaluation of discomfort glare. Lighting Research & Technology. 47(3):379-383. doi:10.1177/1477153515574985.
Fotios S, Cheal C. 2010. Stimulus range bias explains the outcome of preferred-illuminance adjustments. Lighting Research & Technology. 42:433–447. doi:10.1177/1477153509356018.
Fotios S, Logadóttir Á, Cheal C, Christoffersen J. 2011. Using adjustment to define preferred illuminances: Do the results have any value? CIE 27th Session 2011. Sun City, South Africa. July 09-16, 2011.
Galasiu AD, Veitch JA. 2006. Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: A literature review. Energy and Buildings. 38(7):728-742. doi:10.1016/j.enbuild.2006.03.001.
Garland R. 1991. The mid-point on a rating scale: Is it desirable? Marketing Bulletin. 2(3):66-70.
Geerdinck LM. 2012. Glare perception in terms of acceptance and comfort [Master's thesis]. [Eindhoven, The Netherlands]: Eindhoven University of Technology (TUE). 74p.
Geerdinck LM, Van Gheluwe JR, Vissenberg MCJM. 2014. Discomfort glare perception of non-uniform light sources in an office setting. Journal of Environmental Psychology. 39:5-13. doi:10.1016/j.jenvp.2014.04.002.
Gellatly AW, Weintraub DJ. 1990. User reconfigurations of the de boer rating scale for discomfort glare. Ann Arbor, USA: University of Michigan. No. UMTRI-90-20. 23p.
Goovaerts C, Descamps F, Jacobs VA. 2017. Shading control strategy to avoid visual discomfort by using a low-cost camera: A field study of two cases. Building and Environment. 125:26-38. doi:10.1016/j.buildenv.2017.08.030.
Hansen P, Sarey Khanie M, Kuhn TE, Christoffersen J, Wienold J, Andersen M. 2016. Glare caused by contrast between task and immediate surround: An evaluation of luminance distribution in the field of view. CIE 2016 “Lighting Quality and Energy Efficiency”. Melbourne, Australia. March 3–5, 2016.
Hellinga HI. 2013. Daylight and view - the influence of windows on the visual quality of indoor spaces [PhD dissertation]. [Delft, The Netherlands]: Technische Universiteit Delft (TUD). 376p.
Hilz R, Cavonius CR. 1974. Functional organization of the peripheral retina: Sensitivity to periodic stimuli. Vision Research. 14(12):1333-1337. doi:10.1016/0042-6989(74)90006-6.
Hirning MB, Isoardi GL, Cowling I. 2014. Discomfort glare in open plan green buildings. Energy and Buildings. 70:427-440. doi:10.1016/j.enbuild.2013.11.053.
Hirning MB, Isoardi GL, Coyne S, Garcia Hansen VR, Cowling I. 2013. Post occupancy evaluations relating to discomfort glare: A study of green buildings in brisbane. Building and Environment. 59:349-357. doi:10.1016/j.buildenv.2012.08.032.
Hirning MB, Isoardi GL, Garcia-Hansen VR. 2017. Prediction of discomfort glare from windows under tropical skies. Building and Environment. 113:107-120. doi:10.1016/j.buildenv.2016.08.005.

Hirning MB, Lim GH, Reimann GP. 2016. Discomfort glare in energy efficient buildings: A case study in the malaysian context. CIE 2016 “Lighting Quality and Energy Efficiency”. Melbourne, Australia. March 3–5, 2016.

Hopkinson RG. 1957. Evaluation of glare. Illuminating Engineering. 52:329-336.

Hopkinson RG. 1971. Glare from windows - using the glare index in daylighting design. Construction Research Development. 3:23-28.

Hopkinson RG. 1972. Glare from daylighting in buildings. Applied Ergonomics. 3(4):206-215. doi:10.1016/0003-6870(72)90102-0.

Hopkinson RG, Petherbridge P, Longmore J. 1966. Daylighting. London, UK: Butterworth-Heinemann Ltd. 640p.

Huang WJ, Yang Y, Ronnier Luo M. 2017. Discomfort glare caused by white leds having different spectral power distributions. Lighting Research & Technology. doi:10.1177/1477153517704996.

Huang YC, Wang T-H. 2016. Automatic calculation of a new china glare index. Building Simulation & Optimization 2016. Newcastle, UK. September 12-14, 2016.

Inkarojrit V. 2005. Balancing comfort: Occupants’ control of window blinds in private offices [PhD dissertation]. [Berkeley, USA]: University of California (UC). 277p.

Inoue Y, Itoh K. 1989. Methodological study of dynamic evaluation for discomfort glare. Journal of Architecture, Planning and Environmental Engineering. 398:9-19.

Iodice M, Jost S, Dumortier D, Gronfier C. 2017. An experimental protocol to objectively characterize discomfort glare using physiological measurements. CIE 2017 Midterm Meeting. Jeju, South Korea. October 21-28, 2017.

Iwata T, Imai M, Hagiwara H, Akiyama Y, Sekihara M. 2017a. Effects of task and views on discomfort glare from windows. CIE 2017 Midterm Meeting. Jeju, South Korea. October 21-28, 2017.

Iwata T, Kimura K-I, Shukuya M, Takano K. 1990. Discomfort caused by wide-source glare. Energy and Buildings. 15(3/4):391-398. doi:10.1016/0378-7788(90)90013-9.

Iwata T, Nagayoshi K, Osterhaus WKE. 2011a. Discomfort glare index for automated blind control. International Student Energy Summit 2011. Vancouver, Canada. June 09-11, 2011.

Iwata T, Osterhaus W. 2010. Assessment of discomfort glare in daylit offices using luminance distribution images. CIE 2010 "Lighting Quality & Energy Efficiency". Vienna, Austria. March 14-17, 2010.

Iwata T, Osterhaus WKE, Itoh HE. 2011b. Assessment of discomfort glare from windows with venetian blinds using luminance distribution images. CIE 27th Session 2011. Sun City, South Africa. July 09-16, 2011.

Iwata T, Shukuya M, Somekawa N, Kimura K-i. 1992a. Experimental study on discomfort glare caused by windows: Subjective response to glare from a simulated window. Journal of Architecture, Planning and Environmental Engineering. (432):21-33.

Iwata T, Taniguchi T, Sakuma R. 2017b. Automated blind control based on glare prevention with dimmable light in open-plan offices. Building and Environment. 113:232-246. doi:10.1016/j.buildenv.2016.08.034.

Iwata T, Tokura M. 1997. Position index for a glare source located below the line of vision. Lighting Research & Technology. 29:172-178. doi:10.1177/14771535970290030801.

Iwata T, Tokura M. 1998. Examination of the limitations of predicted glare sensation vote (pgsv) as a glare index for a large source: Towards a comprehensive development of discomfort glare evaluation. Lighting Research & Technology. 30(2):81-88. doi:10.1177/096032719803000205.

Iwata T, Tokura M, Shukuya M, Kimura K-i. 1992b. Experimental study on discomfort glare caused by windows: Subjective response to glare from actual windows. Journal of Architecture, Planning and Environmental Engineering. (439):19-31.

Jakubiec JA, Reinhart CF. 2011. The ‘adaptive zone’ – a concept for assessing discomfort glare throughout daylit spaces. Lighting Research & Technology. 44:149-170. doi:10.1177/1477153511420097.

Jakubiec JA, Reinhart CF. 2016. A concept for predicting occupants' long-term visual comfort within daylit spaces. The Journal of the Illuminating Engineering Society. 12(4):185-202. doi:10.1080/15502724.2015.1090880.

Karwowski W. 2006. International encyclopedia of ergonomics and human factors - volume 1. Boca Raton, USA: CRC Press. 3652p.

Kent M, Altomonte S, Tregenza P, Wilson R. 2015a. Time of day, temporal variables and personal factors in the subjective evaluation of glare sensation. PLEA 2015. Bologna, Italy. September 09-11, 2015.

Kent M, Altomonte S, Tregenza PR, Wilson R. 2015b. Discomfort glare and time of day. Lighting Research & Technology. 47:641-657. doi:10.1177/1477153514547291.

Kent M, Altomonte S, Tregenza PR, Wilson R. 2015c. Temporal variables and personal factors in glare sensation. Lighting Research & Technology. 48(6):689-710. doi:10.1177/1477153515578310.

Kent M, Altomonte S, Wilson R, Tregenza PR. 2017a. Temporal effects on glare response from daylight. Building and Environment. 113:49-64. doi:10.1016/j.buildenv.2016.09.002.

Kent M, Fotios S. 2017. Using adjustment to evaluate discomfort glare. Lux Europa 2017. Ljubljana, Slovenia. September 18-20, 2017.

Kent M, Fotios S, Altomonte S. 2017b. Discomfort glare evaluation: The influence of anchor bias in luminance adjustments. Lighting Research & Technology. doi:10.1177/1477153517734280.

Kent MG. 2016. Temporal effects in glare response [PhD dissertation]. [Nottingham, UK]: University of Nottingham. 390p.

Kim J, de Dear R, Cândido C, Zhang H, Arens E. 2013. Gender differences in office occupant perception of indoor environmental quality (ieq). Building and Environment. 70:245-256. doi:10.1016/j.buildenv.2013.08.022.

Kim JT, Shin JY, Yun GY. 2012. Prediction of discomfort glares from windows: Influence of the subjective evaluation of window views. Indoor and Built Environment. 21(1):92-97. doi:10.1177/1420326X11423157.

Kim W, Han H, Kim JT. 2009. The position index of a glare source at the borderline between comfort and discomfort (bcd) in the whole visual field. Building and Environment. 44(5):1017-1023. doi:10.1016/j.buildenv.2008.07.007.

Kim W, Kim JT. 2010. A distribution chart of glare sensation over the whole visual field. Building and Environment. 45(4):922-928. doi:10.1016/j.buildenv.2009.09.013.

Kim W, Kim JT. 2011. A position index formula for evaluation of glare source in the visual field. Indoor and Built Environment. 20(1):47-53. doi:10.1177/1420326x10389267.

Kim W, Kim JT. 2012. A prediction method to identify the glare source in a window with non-uniform luminance distribution. Energy and Buildings. 46:132-138. doi:10.1016/j.enbuild.2011.10.037.

Kim W, Koga Y. 2004. Effect of local background luminance on discomfort glare. Building and Environment. 39(12):1435-1442. doi:10.1016/j.buildenv.2004.05.003.

Kim W, Koga Y. 2005. Glare constant gw for the evaluation of discomfort glare from windows. Solar Energy. 78(1):105-111. doi:10.1016/j.solener.2004.05.020.

Kimura-Minoda T, Ayama M. 2011. Evaluation of discomfort glare from color leds and its correlation with individual variations in brightness sensitivity. Color research and application. 36:286 – 294.

Ko JK, Choi SY. 2017. Contents development for office smart lights. CIE 2017 Midterm Meeting. Jeju, South Korea. October 21-28, 2017.

Konis K. 2014. Predicting visual comfort in side-lit open-plan core zones: Results of a field study pairing high dynamic range images with subjective responses. Energy and Buildings. 77:67-79. doi:10.1016/j.enbuild.2014.03.035.

Kuhn T, Wienold J, Moosmann C. 2013. Daylight glare : Age effects and their impact on glare evaluation. 8th Energy Forum on Solar Building Skins. Bressanone, Italy. November 05-06, 2013.

Laurentin C, Bermtto V, Fontoynont M. 2000. Effect of thermal conditions and light source type on visual comfort appraisal. Lighting Research & Technology. 32(4):223-233. doi:10.1177/096032710003200406.

Lee ES, Clear RD, Fernandes L, Ward G. 2007. Commissioning and verification procedures for the automated roller shade system at the new york times headquarters, new york, new york. Berkeley, USA: Lawrence Berkeley National Laboratory (LBNL). 112p.

Lee JS, Kim BS. 2007. Development of the nomo-graph for evaluation on discomfort glare of windows. Solar Energy. 81(6):799-808. doi:10.1016/j.solener.2006.09.006.

Lien EL, Hammond BR. 2011. Nutritional influences on visual development and function. Progress in Retinal and Eye Research. 30(3):188-203. doi:10.1016/j.preteyeres.2011.01.001.

Lin Y, Liu Y, Sun Y, Zhu X, Lai J, Heynderickx I. 2014. Model predicting discomfort glare caused by led road lights. Optics express. 22(15):8056-8071. doi:10.1364/OE.22.018056.

Linney AS. 2008. Maximum luminances and luminance ratios and their impact on users' discomfort glare perception and productivity in daylit offices [Master's thesis]. [Wellington, New Zealand]: Victoria University of Wellington. 186p.

Logadóttir Á, Christoffersen J, Fotios S. 2011. Investigating the use of an adjustment task to set the preferred illuminance in a workplace environment. Lighting Research & Technology. 43(4):403-422. doi:10.1177/1477153511400971.

Logadóttir Á, Fotios S, Christoffersen J, Hansen SS, Corell DD, Dam-Hansen C. 2013. Investigating the use of an adjustment task to set preferred colour of ambient illumination. Color research and application. 38(1):46–57. doi:10.1002/col.20714.

Loughman J, Akkali MC, Beatty S, Scanlon G, Davison PA, O'Dwyer V, Cantwell T, Major P, Stack J, Nolan JM. 2010. The relationship between macular pigment and visual performance. Vision Research. 50(13):1249-1256. doi:10.1016/j.visres.2010.04.009.

Luckiesh M, Guth SK. 1949. Brightnesses in visual field at borderline between comfort and discomfort (bcd). National Technical Conference of the Illuminating Engineering Society. French Lick, USA. September 20-23, 1949.

Lulla AB, Bennett CA. 1981. Discomfort glare: Range effects. The Journal of the Illuminating Engineering Society. 10(2):74-80. doi:10.1080/00994480.1980.10748591.

MacGowan D, Aspinall P, Newman P, Russell T, Lakowski R. 1988. Visual quality characteristics of the working environment. Glasgow, UK: Inter-Institutional Research Programme.

MacGowan D, Emery AF. 1986. Window architectonics in the automated office. 10th Triennial Congress of the International Council for Building Research. Washington, USA. September 22-26, 1986.

MacLeod CM. 1991. Half a century of research on the stroop effect: An integrative review. Psychological Bulletin. 109(2):163-203. doi:10.1037/0033-2909.109.2.163.

Mainster MA, Turner PL. 2012. Glare's causes, consequences, and clinical challenges after a century of ophthalmic study. American Journal of Ophthalmology. 153(4):587-593. doi:10.1016/j.ajo.2012.01.008.

Mangkuto RA, Kurnia KA, Azizah DN, Atmodipoero RT, Soelami FXN. 2017. Determination of discomfort glare criteria for daylit space in indonesia. Solar Energy. 149:151-163. doi:10.1016/j.solener.2017.04.010.

Mochizuki E, Iwata T. 2005. Discomfort glare caused by a window screen with non- uniform luminance distribution. Lux Pacifica 2005. Cairns, Australia. July 24-26, 2005.

Narisada K, Schreuder D. 2004. Light pollution handbook. Groningen, The Netherlands: Springer Netherlands. 966p.

Nazzal AA. 2005. A new evaluation method for daylight discomfort glare. International Journal of Industrial Ergonomics. 35(4):295-306. doi:10.1016/j.ergon.2004.08.010.

Ngai P, Boyce P. 2000. The effect of overhead glare on visual discomfort. The Journal of the Illuminating Engineering Society. 29(2):29-38. doi:10.1080/00994480.2000.10748315.

Nicol F, Wilson M, Chiancarella C. 2006. Using field measurements of desktop illuminance in european offices to investigate its dependence on outdoor conditions and its effect on

occupant satisfaction, and the use of lights and blinds. Energy and Buildings. 38(7):802-813. doi:10.1016/j.enbuild.2006.03.014.
Osterhaus WKE. 2001. Discomfort glare from daylight in computer offices: What do we really know? Lux Europa 2001. Reykjavik, Iceland. June 17-20, 2011.
Osterhaus WKE. 2008. Analysis of luminance histograms for the assessment of discomfort glare in daylit offices. Balkan Light 2008. Ljubljana, Slovenia. October 07-09, 2008.
Osterhaus WKE. 2009. Design guidelines for glare-free daylit work environments. Lux Europa 2009. Istanbul, Turkey. September 09-11, 2009.
Osterhaus WKE, Bailey IL. 1992. Large area glare sources and their effect on discomfort and visual performance at computer workstations. 1992 IEEE Industry Applications Society Annual Meeting. Houston, USA. October 04-09, 1992.
Paulsson L-E, Sjostrand J. 1980. Contrast sensitivity in the presence of a glare light - theoretical concepts and preliminary clinical studies. Investigative Ophthalmology & Visual Science. 19(4):401-406. doi:0146-0404/80/040401+06$00.60/0.
Petherbridge P, Hopkinson RG. 1950. Discomfort glare and the lighting of buildings. Lighting Research & Technology. 15(2):39-79. doi:10.1177/147715355001500201.
Pierson C, Piderit MB, Wienold J, Bodart M. 2017. Discomfort glare from daylighting: Influence of culture on discomfort glare perception. CIE 2017 Midterm Meeting. Jeju, South Korea. October 21-28, 2017.
Pulpitlova J, Detkova P. 1993. Impact of the cultural and social background on the visual perception in living and working perception. International Symposium on Design of Amenity. Fukuoka, Japan. October 05-09, 1993.
Rea MS. 1982. Calibration of subjective scaling responses. Lighting Research & Technology. 14(3):121-129.
Rodriguez RG, Pattini A. 2014. Tolerance of discomfort glare from a large area source for work on a visual display. Lighting Research & Technology. 46(2):157-170. doi:10.1177/1477153512470386.
Rodriguez RG, Yamín Garretón JA, Pattini AE. 2016. Glare and cognitive performance in screen work in the presence of sunlight. Lighting Research & Technology. 48(2):221-238. doi:10.1177/1477153515577851.
Sarey Khanie M, Jia Y, Wienold J, Andersen M. 2015. A sensitivity analysis on glare detection parameters. BS2015-14th International Conference of the International Building Performance Simulation Association. Hyderabad, India. December 07-09, 2015.
Sarey Khanie M, Stoll J, Einhäuser W, Wienold J, Andersen M. 2017. Gaze and discomfort glare, part 1: Development of a gaze-driven photometry. Lighting Research & Technology. 49(7):845-865. doi:10.1177/1477153516649016.
Saur RL. 1969. Influence of physiological factors on discomfort glare level. Optometry & Vision Science. 46(5):352-357.
Scheir GH, Hanselaer P, Bracke P, Deconinck G, Ryckaert WR. 2015. Calculation of the unified glare rating based on luminance maps for uniform and non-uniform light sources. Building and Environment. 84(0):60-67. doi:10.1016/j.buildenv.2014.10.027.
Scheir GH, Hanselaer P, Ryckaert WR. 2017. Pupillary light reflex and receptive field calculation of visual discomfort for different spatial frequencies and luminance steps. CIE 2017 Midterm Meeting. Jeju, South Korea. October 21-28, 2017.
Sekihara M, Imai M, Hagiwara H, Akiyama Y, Taniguchi T, Iwata T. 2016. Effect of task on discomfort glare from windows. 9th CJK Lighting Conference. Busan, Korea. August 18-19, 2016.
Shen E, Hu J, Patel M. 2014. Energy and visual comfort analysis of lighting and daylight control strategies. Building and Environment. 78:155-170. doi:10.1016/j.buildenv.2014.04.028.
Shin JY, Yun GY, Kim JT. 2012. View types and luminance effects on discomfort glare assessment from windows. Energy and Buildings. 46:139-145. doi:10.1016/j.enbuild.2011.10.036.

Siah WF, O'Brien C, Loughman JJ. 2017. Macular pigment is associated with glare-affected visual function and central visual field loss in glaucoma. British Journal of Ophthalmology. doi:10.1136/bjophthalmol-2017-310215.

Sivak M, Flannagan MJ, Ensing M, Simmons CJ. 1989. Discomfort glare is task dependent. Ann Arbor, USA: University of Michigan. No. UMTRI-89-27. 18p.

Sivak M, Flannagan MJ, Traube EC, Kojima S. 1997. The influence of stimulus duration on discomfort glare for persons with and without visual correction. Ann Arbor, USA: University of Michigan. No. UMTRI-97-23. 22p.

Sivak M, Schoettle B, Minoda T, Flannagan MJ. 2005. Short-wavelength content of led headlamps and discomfort glare. The Journal of the Illuminating Engineering Society. 2(2):145-154. doi:10.1582/LEUKOS.2005.02.02.006.

Stone PT, Harker SDP. 1973. Individual and group differences in discomfort glare responses. Lighting Research & Technology. 5(1):41-49. doi:10.1177/096032717300500106.

Stringham JM, Fuld K, Wenzel AJ. 2003. Action spectrum for photophobia. Journal of the Optical Society of America. 20(10):1852-1858. doi:10.1364/JOSAA.20.001852.

Stringham JM, Fuld K, Wenzel AJ. 2004. Spatial properties of photophobia. Investigative Ophthalmology & Visual Science. 45(10):3838-3848. doi:10.1167/iovs.04-0038.

Stringham JM, Garcia PV, Smith PA, McLin LN, Foutch BK. 2011. Macular pigment and visual performance in glare: Benefits for photostress recovery, disability glare, and visual discomfort. Investigative Ophthalmology & Visual Science. 52:7406-7415. doi:10.1167/iovs.10-6699.

Subova A, Kittler R, MacGowan D. 1991. Results of ongoing experiments on subjective response to discomfort glare. Journal of the illuminating Engineering Institute of Japan. 75(Appendix):129-130. doi:10.2150/jieij1980.75.Appendix_129.

Sweater-Hickcox K, Narendran N, Bullough JD, Freyssinier JP. 2012. Effect of different colored background lighting on led discomfort glare perception. Twelfth International Conference on Solid State Lighting and Fourth International Conference on White LEDs and Solid State Lighting. San Diego, USA. August 12-16, 2012. doi:10.1117/12.968192.

Tashiro T, Kawanobe S, Kimura-Minoda T, Kohko S, Ishikawa T, Ayama M. 2015. Discomfort glare for white led light sources with different spatial arrangements. Lighting Research & Technology. 47:316–337. doi:10.1177/1477153514532122.

Tokura M, Iwata T, Shukuya M. 1996. Experimental study on discomfort glare caused by windows: Development of a method for evaluating discomfort glare from a large light source. Journal of Architecture, Planning and Environmental Engineering. (489):17-25.

Torres S, Lo Verso VRM. 2015. Comparative analysis of simplified daylight glare methods and proposal of a new method based on the cylindrical illuminance. Energy Procedia. 78:699-704. doi:10.1016/j.egypro.2015.11.074.

Tuaycharoen N. 2011. Windows are less glaring when there is a preferred view. Built-Environment Sri Lanka. 9-10(1-2):45–55.

Tuaycharoen N, Tregenza PR. 2005. Discomfort glare from interesting images. Lighting Research & Technology. 37(4):329-338. doi:10.1191/1365782805li147oa.

Tuaycharoen N, Tregenza PR. 2007. View and discomfort glare from windows. Lighting Research & Technology. 39(2):185-200. doi:10.1177/1365782807077193.

Tyukhova YI. 2015. Discomfort glare from small, high luminance light sources in outdoor nighttime environments [PhD dissertation]. [Lincoln, USA]: University of Nebraska - Lincoln. 295p.

van Bommel W. 2015. Road lighting: Fundamentals, technology and application. Cham, Switzerland: Springer International Publishing. 343p.

Van Den Wymelenberg K. 2012. Evaluating human visual preference and performance in an office environment using luminance-based metrics [PhD dissertation]. [Washington, USA]: University of Washington (UW). 346p.

Van Den Wymelenberg K. 2014. Visual comfort, discomfort glare, and occupant fenestration control: Developing a research agenda. The Journal of the Illuminating Engineering Society. 10(4):207-221. doi:10.1080/15502724.2014.939004.

Van Den Wymelenberg K, Inanici M. 2014. A critical investigation of common lighting design metrics for predicting human visual comfort in offices with daylight. The Journal of the Illuminating Engineering Society. 10(3):145-164. doi:10.1080/15502724.2014.881720.

Van Den Wymelenberg K, Inanici M. 2016. Evaluating a new suite of luminance-based design metrics for predicting human visual comfort in offices with daylight. The Journal of the Illuminating Engineering Society. 12:113-138. doi:10.1080/15502724.2015.1062392.

Van Den Wymelenberg K, Inanici M, Johnson P. 2010. The effect of luminance distribution patterns on occupant preference in a daylit office environment. The Journal of the Illuminating Engineering Society. 07(02):103-122. doi:10.1080/19401493.2015.1058421.

Vásquez NG, Ruttkay Pereira FO, Pires MO, Moraes LN. 2016. Investigating a method to dynamic assessment of glare using the hdr technique. PLEA 2016. Los Angeles, USA. July 11-13, 2016.

Veitch JA, Newsham GR. 2000. Preferred luminous conditions in open-plan offices: Research and practice recommendations. Lighting Research & Technology. 32(4):199-212. doi:10.1177/096032710003200404.

Velds M. 2000. Assessment of lighting quality in office rooms with daylighting systems [PhD dissertation]. [Delft, The Netherlands]: Technische Universiteit Delft (TUD). 231p.

Völker S, Freyer M, Raphael S, Meyborg M. 2017. Influence factors for discomfort glare of headlamps and a new model for its estimation. CIE 2017 Midterm Meeting. Jeju, South Korea. October 21-28, 2017.

Vos J, Van Bergem-Jansen PM. 1995. Greenhouse lighting side-effects: Community reaction. Lighting Research & Technology. 27(1):45-51. doi:10.1177/14771535950270010301.

Ward G. Radiance findglare program. 1993. [accessed September 27, 2017]. http://radsite.lbl.gov/radiance/man_html/findglare.1.html.

Waters CE, Mistrick RG, Bernecker CA. 1995. Discomfort glare from sources of nonuniform luminance. The Journal of the Illuminating Engineering Society. 24(2):73-85. doi:10.1080/00994480.1995.10748120.

Wei M, Houser KW, Orland B, Lang DH, Ram N, Sliwinski MJ, Bose M. 2014. Field study of office worker responses to fluorescent lighting of different cct and lumen output. Journal of Environmental Psychology. 39:62-76. doi:10.1016/j.jenvp.2014.04.009.

Weijters B, Cabooter E, Schillewaert N. 2010. The effect of rating scale format on response styles: The number of response categories and response category labels. International Journal of Research in Marketing. 27(3):236-247.

Wienold J. 2009a. Daylight glare in offices [PhD dissertation]. [Freiburg, Germany]: Universität Karlsruhe (TH). 136p.

Wienold J. 2009b. Workshop glare analysis of hdr images. 8th International Radiance Workshop. Boston, USA. October 21-23, 2009.

Wienold J, Christoffersen J. 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of ccd cameras. Energy and Buildings. 38(7):743-757. doi:10.1016/j.enbuild.2006.03.017.

Wirtschafter JD, Bourassa CM. 1966. Binocular facilitation of discomfort with high luminances. Archives of Ophthalmology. 75:683–688.

Wolska A, Sawicki D. 2014. Evaluation of discomfort glare in the 50+ elderly: Experimental study. International Journal of Occupational Medicine and Environmental Health. 27(3):444-459. doi:10.2478/s13382-014-0257-9.

Wright KPJ, Badia P, Myers BL, Plenzler SC, Hakel M. 1997. Caffeine and light effects on nighttime melatonin and temperature levels in sleep-deprived humans. Brain Research. 747(1):78-84. doi:10.1016/S0006-8993(96)01268-1.

Yamin Garretón J, Rodriguez R, Pattini A. 2015. Effects of perceived indoor temperature on daylight glare perception. Building Research & Information. 44(8):1-14. doi:10.1080/09613218.2016.1103116.

Yang Y, Ronnier Luo M, Huang WJ. 2016. Assessing glare, part 3: Glare sources having different colours. Lighting Research & Technology. doi:10.1177/1477153516676640.

Yang Y, Ronnier Luo M, Ma SN. 2017. Assessing glare. Part 2: Modifying unified glare rating for uniform and non-uniform led luminaires. Lighting Research & Technology. 49:727–742. doi:10.1177/1477153516642622.

Zhang J, Tu Y, Liu L, Wang L, Peng S, Heynderickx I. 2013. Effect of the correlated color temperature of light on overhead glare in offices. SID Display Week. Vancouver, Canada. May 19-24, 2013.

Appendix I

Journal Article in Buildings

The appended article is the open-access study article published in Buildings [Pierson et al. 2018a].

buildings

MDPI

Article

Daylight Discomfort Glare Evaluation with Evalglare: Influence of Parameters and Methods on the Accuracy of Discomfort Glare Prediction

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Abstract: Nowadays, discomfort glare indices are frequently calculated by using evalglare. Due to the lack of knowledge on the implications of the methods and parameters of evalglare, the default settings are often used. But wrong parameter settings can lead to inappropriate glare source detection and therefore to invalid glare indices calculations and erroneous glare classifications. For that reason, this study aims to assess the influence of several glare source detection methods and parameters on the accuracy of discomfort glare prediction for daylight. This analysis uses two datasets, representative of the two types of discomfort glare: saturation and contrast glare. By computing three different statistical indicators to describe the accuracy of discomfort glare prediction, 63 different settings are compared. The results suggest that the choice of an evalglare method should be done when considering the type of glare that is most likely to occur in the visual scene: the task area method should be preferred for contrast glare scenes, and the threshold method for saturation glare scenes. The parameters that should be favored or avoided are also discussed, although a deeper understanding of the discomfort glare mechanism and a clear definition of a glare source would be necessary to reliably interpret these results.

Keywords: evalglare; discomfort glare; glare source detection; glare evaluation; parametric analysis

1. Introduction

According to the International Commission on Illumination (CIE), glare is defined as the "*condition of vision in which there is discomfort* [discomfort glare] *or a reduction in the ability to see significant objects* [disability glare]*, or both, due to an unsuitable distribution or range of luminances or to extreme contrasts in space or time*" [1]. When studying discomfort glare nowadays, the most common method is to compare subjective glare ratings that are made on discomfort glare scales, and the values of discomfort glare indices calculated from measured physical quantities. There are four main physical quantities, on which discomfort glare indices are based [1]: the luminance of the glare source(s) in the field of view, the solid angle of the glare source(s), the luminance of the background, and the position index of the glare source(s). To measure these quantities efficiently in situ, High Dynamic Range (HDR) imaging technique is used to create a 180° luminance map containing the subject's field of view. Discomfort glare indices are then calculated afterward on the basis of these luminance maps. Alternatively, such 180° luminance maps can also be generated through simulation tools. The calculation of discomfort glare indices based on a luminance map is therefore an essential step and an inherent part of discomfort glare studies.

The difficulty of this step, however, lies in the identification of the glare source(s) in the field of view. If a glare source has been identified in the 180° luminance map, its solid angle, position index,

and luminance can be easily determined. The background luminance can also be quickly evaluated as the average luminance of the luminance map, excluding the glare source. But, as reported in [2], the definition of the glare source is still ambiguous, and there is no universal method of identifying one. The most common methods that are currently used are the ones implemented in evalglare. Evalglare is a Radiance-based tool developed by J. Wienold as part of a larger glare study with J. Christoffersen [3], during which they created the Daylight Glare Probability (DGP) index. This tool requires a 180° luminance map containing the field of view as input, then runs an algorithm to detect glare sources, and finally calculates different discomfort glare indices from the detected glare sources [4–6]. The output of evalglare is therefore a list of discomfort glare indices values that are calculated on the basis of the glare sources detected by the algorithm in the luminance map. Evalglare is a powerful tool that makes discomfort glare indices calculations easier and quicker, which is the reason why it is so widely used.

Evalglare algorithm enables the use of three different methods for glare source detection: the factor method, the threshold method, and the task area method, which will be explained later. The task area method is the one that provided the best results for Wienold's study [7] in terms of correlation with subjective glare ratings. However, the factor method is more widely used, as a consequence of being the default method implemented in evalglare. What is more, the factor method is also the default method when performing a point-in-time glare analysis in the daylight-simulation software DIVA-for-Rhino [8], and there exists no option in the user-friendly interface to modify it.

Moreover, several options and parameters can be changed in evalglare, which modify the glare source detection algorithm. But, these options and parameters are seldom used as compared to the default or recommended ones, probably because of the lack of knowledge about their influence on glare sources detection. Surprisingly, evalglare tool has never been the object of a validation study—other than Wienold and Christoffersen's study—although it has been now used for over 10 years. There exist no recommendations based on scientific evidence on which methods should be preferred in which cases, and which options should be applied for which conditions.

Therefore, the aim of this study is to investigate the effect of different evalglare methods and parameters on discomfort glare prediction. Although it would be interesting to look at the sensitivity of discomfort glare indices values when varying evalglare methods and parameters, the focus of this study is about determining which method and parameters offer the best discomfort glare prediction in comparison with subjective glare ratings. Two datasets are used in this study, comprising, for each glare evaluation, a subjective glare rating and a 180° luminance map containing the subject's field of view. Each dataset is representative of a discomfort glare type, i.e., contrast glare or saturation glare. By varying evalglare options—combination of evalglare methods and parameters—when calculating the discomfort glare indices based on the luminance maps, the options that offer the best prediction of subjective glare ratings for the two types of glare may be identified.

2. Datasets

Two datasets containing daylight discomfort glare evaluations are used for this study. The demographic information of these datasets is available in Table 1.

Table 1. Demographic and general information of field and laboratory datasets.

Experiment	Subjects	Men/Women Ratio (%)	Mean Age (SD)	Glare Evaluations	4-Point Glare Scale	Glare Rating Ratio (%)
Field study	82	43/57	36 (11)	141	No discomfort A small discomfort A moderate discomfort A large discomfort	65 20 11 4
Laboratory study	41	73/27	26 (3)	180	Imperceptible Noticeable Disturbing Intolerable	53 30 17 1

The first dataset was collected during a field study that was conducted in Louvain-la-Neuve (Belgium) from June to August 2017. 82 subjects participated in the study, which consisted of collecting almost simultaneously subjective glare ratings and 180° luminance maps containing the subject's field of view in their real office. The study took place in several university buildings, for office desks that are located next to an east-, west-, or south-oriented window. Each subject did two glare evaluations—the first one for the situation they were working in, and the second one for the situation with opened shading devices and artificial lighting turned off—resulting in a total of 164 evaluations. Despite the fact that the field study was conducted under clear sky conditions, 23 evaluations had to be disregarded due to unstable lighting conditions. The subjective glare ratings were preceded by a short visual task, and were made on a 4-point scale, on which the subject has to evaluate his/her perception of discomfort due to glare as either "No discomfort", "A small discomfort", "A moderate discomfort", or "A large discomfort". The detailed experiment protocol has been published in [9].

The second dataset was collected during a laboratory study that was conducted in two office-like cells in Freiburg (Germany) in the spring/summer/autumn months between 2008 and 2011. In total, 150 subjects had to perform five visual tasks, each followed by a discomfort glare rating, for maximum four different visual scenes—the shading device was varied—at two different times of the day—morning and afternoon. However, only data from 41 subjects and from one of the five visual tasks, namely the typing task, collected in the spring and summer months were available and used in this study, resulting in a total of 180 glare evaluations. The laboratory study was conducted under clear sky conditions, and the office-like cells were rotated so that the sun direction was perpendicular to the façade. The discomfort glare rating was done on a different 4-point glare scale, on which the subject was asked to evaluate his/her glare perception as "Imperceptible", "Noticeable", "Disturbing", or "Intolerable". Simultaneously with the discomfort glare rating, a 180° luminance map was created with the luminance camera positioned next to the subject's head, at eye level. More details about this laboratory study have been published in [10].

The choice of using two different datasets was made so that a greater variety of visual scenes is studied, especially the two types of discomfort glare, namely the contrast and saturation glare. The lighting conditions between the two studies are very different, as can be seen in Figure 1. Vertical illuminance at the eye level is much higher in the case of the laboratory study, with a median illuminance level above 2000 lux, when compared to a median illuminance level of around 500 lux for the field study. This implies that when discomfort glare was perceived in the field study, discomfort most probably was caused from high contrast between the glare source and the background. On the opposite, when discomfort glare was perceived in the laboratory study, discomfort was most probably due to a too bright visual scene. Therefore, most discomfort glare situations in the field study were caused by contrast glare, whereas discomfort glare situations in the laboratory study were mainly caused by saturation glare. These two datasets can therefore be used as the representatives of the two main types of discomfort glare. Moreover, the two studies have several differences in their experimental design, besides being a field or laboratory study type. One of the main differences is the use of two different glare rating scales for the subjective evaluation of discomfort glare (Table 1). Another main difference is that, in the field study, the HDR image is captured directly after the subjective glare rating, but at the exact same place of the subject's eyes, while in the laboratory study, the HDR image is captured at the exact same time than the subjective glare rating, but next to the subject's head. These differences make the two datasets representative of many discomfort glare studies, and they enable the results to be relevant for a large number of future studies. These differences also hinder the comparison of the accuracy of discomfort glare prediction between the datasets, which is not the subject of this study.

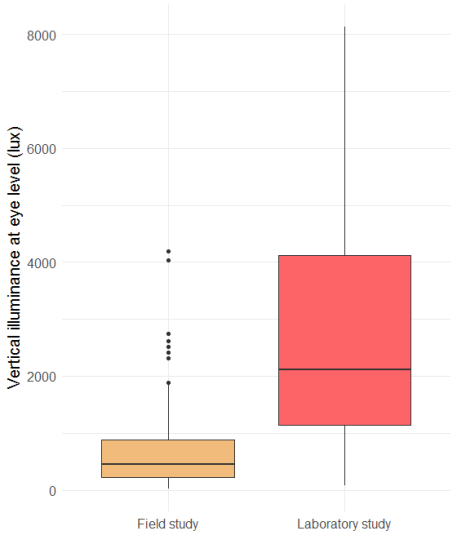


Figure 1. Boxplots of vertical illuminance at eye level between the field study and the laboratory study.

3. Methodology

When using evalglare, the choice of a method and parameters influence glare source detection in a luminance map. The detected glare sources, in turn, influence discomfort glare indices calculation. At last, the accuracy of discomfort glare prediction varies according to these discomfort glare indices. To determine which method and which parameters of evalglare are the most appropriate for each type of discomfort glare research, the reported effects of the choice of a method and parameters in evalglare on the accuracy of discomfort glare prediction is investigated. However, the effects of this choice on the in-between steps, namely the glare source detection and the discomfort glare indices calculation, will not be examined here.

63 different evalglare options—each option is a different combination of one of the three evalglare methods and different parameters—for detecting glare sources in a luminance map are tested. The accuracy of discomfort glare prediction of these 63 different options is evaluated through three different statistical approaches for each of the two datasets. The 63 studied evalglare options, as well as the three statistical approaches are explained in Sections 3.1 and 3.2.

3.1. Studied Evalglare Methods and Parameters

The three different methods implemented in evalglare are, as named in this article, the factor method, the threshold method, and the task area method.

The algorithm of the factor method detects in the 180° luminance map all of the pixels having a luminance value higher than the mean luminance of the luminance map multiplied by a certain factor. These pixels are treated as the glare sources. In this study, 4 different factors were tested: a multiplying factor of 5 (b5), which is the default method in evalglare, 6 (b6), 7 (b7), and 8 (b8).

The algorithm of the threshold method detects in the 180° luminance map all pixels having a luminance value that is higher than a certain threshold, and treat these pixels as the glare sources. In the literature, several thresholds have been used throughout the years [11–15], but the three most common ones are a threshold of 1000 cd/m^2 (b1000), of 2000 cd/m^2 (b2000), and of 4000 cd/m^2 (b4000).

The algorithm of the task area method detects in the 180° luminance map all pixels having a luminance value higher than the mean luminance of a defined task area in the luminance map multiplied by a certain factor. This last method requires prior definition of a task area. The recommended multiplying factor for the task area method in evalglare is 5. Three other factors will also be tested in this study, resulting in multiplying factors of 3 (t3), 4 (t4), 5 (t5), and 6 (t6).

Four other evalglare parameters are investigated in this study. First, the background luminance definition will be tested, since there exist two different definitions of this background luminance. The first definition is the one that is provided by the CIE, which approximates the background luminance as the indirect vertical illuminance of the visual field divided by π (_def). The second one is the mathematical definition, i.e., the mathematical average of the luminance values in the luminance map excluding the glare sources (_Lb). Secondly, the search radius, which is the distance within which two glaring pixels are included in the same glare source, will be varied. The default value of the search radius, 0.2 (_def), as well as one smaller value -0.06 (_r0.06)—and one larger value -0.3 (_r0.3)—will be tested. The task area size, which is only required when using the task area method, will then be varied as well. The task area is defined as the area where the subject's eyes are focused. The usual task area size has an opening angle of around 60° (_def) to correspond to the ergorama, i.e., the area around the computer screen and keyboard. A smaller task area size $-30°$ (_ta0.52)—including only the computer screen, and a larger size $-90°$ (_ta1.57)—will also be tested. At last, the smooth parameter, which should mainly be used when the visual scene includes blinds, is investigated. This parameter includes non-glaring pixels (pixels of blind slats for instance) nested in a glare source (a glare source seen through the blinds for instance) to the glare source, smoothing the glare source area. The accuracy of discomfort glare prediction will thus be tested with (_sm) and without (_def) the smooth parameter.

Table 2 summarizes all 63 evalglare options that were tested in this study and provides an example of the differences in glare sources detection between these options. The colored parts in the images correspond to the different detected glare sources. The choice of colors is randomly made by evalglare algorithm and has no signification.

Table 2. Example of a visual scene from the lab study of differences in glare source detection for all of the evalglare options tested.

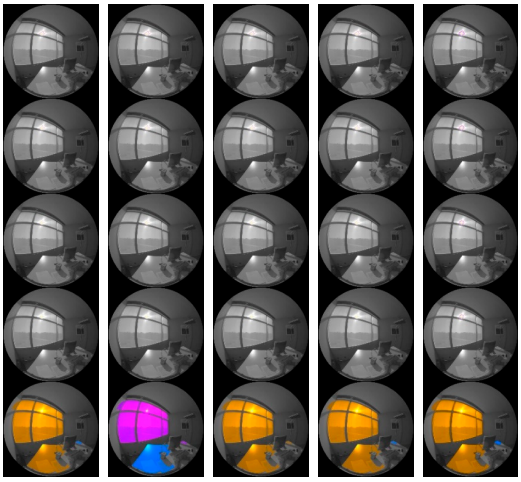
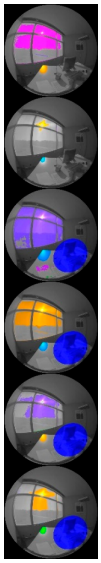
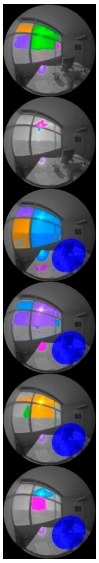
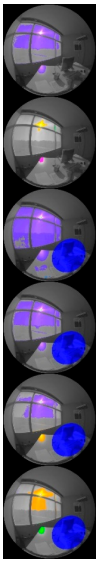
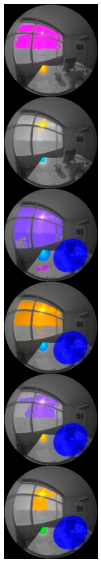
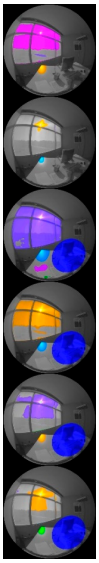
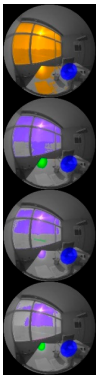
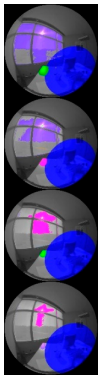
	def	r0.06	r0.3	Lb	sm	ta0.52	ta1.57
b5						/	/
b6						/	/
b7						/	/
b8						/	/
b1000						/	/

Table 2. *Cont.*

	def	r0.06	r0.3	Lb	sm	ta0.52	ta1.57
b2000						/	/
b4000						/	/
t3							
t4							
t5							
t6							

3.2. Statistical Approaches

Instead of looking at the direct effects of the 63 different evalglare options on glare source detection or on discomfort glare indices calculation, the reported effects on the accuracy of discomfort glare prediction is studied. The accuracy of discomfort glare prediction can be defined as how well a discomfort glare index can predict the corresponding subjective glare rating, i.e., how well this index correlates with the rating made by the subjects.

Since the aim of this study is to produce results that are widely interpretable, it was decided not to choose only one daylight discomfort glare index, but to base the statistical analyses on the five most commonly used daylight discomfort glare indices, namely the Daylight Glare Probability (DGP) [3], the Discomfort Glare Index (DGI) [16], the CIE Glare Index (CGI) [17], the modified Discomfort Glare Index (DGImod) [18], and the Unified Glare Probability (UGP) [19]. These discomfort glare indices are calculated with each of the 63 evalglare options, and for both datasets. The grand means, i.e., the means throughout the 63 evalglare options of the mean glare indices values, are reported in Table 3.

Table 3. Grand mean of each discomfort glare index value for both datasets.

Experiment	DGP	DGI	CGI	DGImod	UGP
Field study	0.19	11.55	12.18	17.76	0.49
Laboratory study	0.33	11.82	12.6	18.85	0.5

Three statistical approaches have been chosen to compare the accuracy of discomfort glare prediction resulting from the 63 evalglare options. For each approach, an indicator of the relationship between the subjective glare ratings and each of the five discomfort glare indices calculated with the 63 evalglare options is evaluated. These indicators are the Spearman correlation coefficient, the Area

Under the Curve (AUC) of a binary logistic regression, and the corrected Akaike's Information Criterion (AICc) of an ordinal logistic regression. Since 63 evalglare options are compared in this study, the p-values of the Spearman test and the logistic regressions are adjusted with a Bonferroni correction. This correction, which can be applied without any distributional assumptions, reduces the risk of a type I error, i.e., getting a significant result due to chance. These indicators are then compared between the 63 evalglare options. This comparison is first made visually through boxplots, and then statistically through significance testing or threshold checking. Each of the five discomfort glare indices is considered in the comparison, which is done separately for the two datasets.

3.2.1. Spearman Correlation Coefficient

The first statistical approach is based on Spearman correlation. Spearman correlation was chosen over Pearson correlation because one of the two variables—the 4-point glare scale—is an ordinal variable, and Spearman correlation uses the rank of the data points instead of their value [20]. The correlation coefficient, with their Bonferroni adjusted p-values, were evaluated between each of the five discomfort glare indices calculated with the 63 evalglare options, and the subjective ratings made on the 4-point glare rating scale for both datasets. The Spearman correlation coefficient is used as the first indicator of the accuracy of discomfort glare prediction: the larger the coefficient, the better the prediction. In the literature, absolute thresholds have been used to define the magnitude of a correlation coefficient: a coefficient of 0.2 is considered to be a practically significant effect, one of 0.5 a moderate effect, and one of 0.8 a strong effect [21].

To determine whether the difference between two correlation coefficients is statistically significant, several significance tests exist. In this study, the cocor package in R [22] was used to apply 10 different significance tests. These tests are designed to compare two correlation coefficients based on dependent groups (the two correlation coefficients are evaluated on the same dataset) with overlapping variables (one of the two variables of the correlation is the same). The significant difference score between two coefficients, i.e., between two evalglare options, is given one point if the result of the test comparing these two coefficients is found to be statistically significant. The significance of the difference between each evalglare option is then evaluated on this score, going from 0 to 50, since 10 significance tests are performed for each of the five discomfort glare indices.

3.2.2. Area Under the Receiver Operating Characteristic (ROC) Curve of Binomial Logistic Regression Models

The second statistical approach requires the computation of binary logistic regression models, which use a binary variable as the dependent variable. Therefore, the two 4-point glare scales are first transformed into binary scales: no discomfort-discomfort (Figure 2).

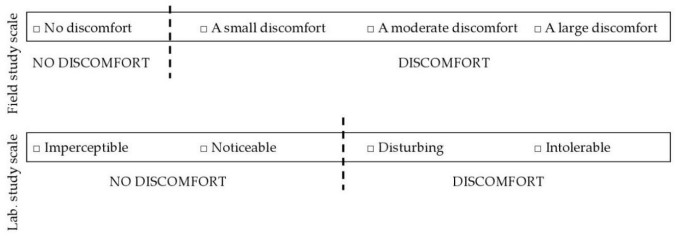


Figure 2. Binary transformation (no discomfort–discomfort) of the subjective glare scales used in the field and laboratory studies.

Binary logistic regression models are then computed, with the binary discomfort glare rating as the dependent variable, and each one of the five discomfort glare indices calculated with each one of

the 63 evalglare options as the independent variable. The binary logistic regression models estimate the probability that discomfort due to glare is perceived given the value of the explanatory variable, i.e., the discomfort glare index. Bonferroni correction is applied when checking the significance of each logistic regression model.

To compare the 63 evalglare options, the Area Under the Receiver Operating Characteristic (ROC) Curve (AUC), specific to each binary logistic regression model, is used. The ROC curve of a logistic regression model illustrates its diagnostic ability for each possible discrimination threshold. In other words, the ROC curve can be plotted in such a way that each point of the curve represents a different cut-off value, and the x and y coordinates of this point correspond, respectively, to the False Positive Rate (FPR) and the True Positive Rate (TPR) of the model when using this cut-off value (Figure 3). The AUC of a logistic regression model is the area comprised beneath the ROC curve of the model. The larger the AUC, the better the model, as the probability of good detection (TPR) is maximized, whereas the probability of false alarm (FPR) is minimized. The AUC of each binary logistic regression model is used as the second indicator of the accuracy of discomfort glare prediction. In the literature, the absolute thresholds for AUC are used to define the quality of discrimination of a model: an AUC < 0.6 corresponds to a failing model, an AUC ≥ 0.6 to a poor model, an AUC ≥ 0.7 to an acceptable model, and an AUC ≥ 0.8 to an excellent model [23,24].

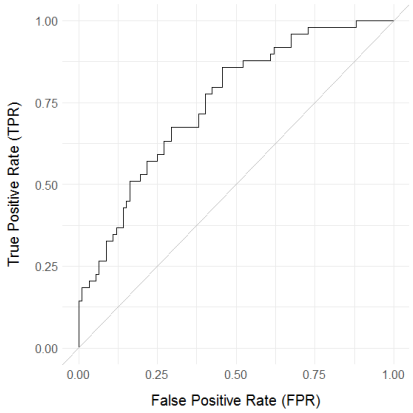


Figure 3. Graph of the Receiver Operating Characteristic (ROC) curve corresponding to the binary logistic regression model computed for the Daylight Glare Probability (DGP) index calculated with t4_def evalglare option on the field study dataset (AUC = 0.7496).

Similarly to the comparison of Spearman correlation coefficients, significance tests can be applied to determine whether the difference between two AUC is statistically significant. Three different significance tests [25–27] were applied in this study through the pROC package in R. These tests are designed to compare the AUC of two paired ROC curves, namely ROC curves of logistic regression models built on two variables from the same dataset. Using the same scoring system as for the Spearman indicator, the significance of the difference between each evalglare option resulting from the AUC approach is evaluated on a score going from 0 to 15, since three significance tests are performed for each of the five discomfort glare indices.

3.2.3. Corrected Akaike's Information Criterion of Ordinal Logistic Regression Models

The last statistical approach involves the computation of ordinal logistic regression models. Ordinal logistic regression models can be interpreted as an extension of the binary logistic regression

models, which allows for more than two response categories. These models can therefore be computed directly using a 4-point glare scale as the dependent variable. Instead of estimating the probability that discomfort due to glare will be perceived, the ordinal logistic regression models measure how likely the response is to fall below one of the three thresholds of the 4-point scale, given the value of the independent variable, i.e., the discomfort glare index. Ordinal logistic regression models are computed for each one of the five discomfort glare indices that were calculated with each one of the 63 evalglare options. Bonferroni correction is applied when checking the significance of each model.

By comparing how well the ordinal models fit to the data, the 63 evalglare methods can be compared, so that the evalglare option providing the best accuracy of discomfort glare prediction can be highlighted. One common way of comparing the fit of ordinal logistic regression models is to evaluate their corrected Akaike's Information Criterion (AICc). The AICc is used as an indicator of the relative information that is lost when a given model is chosen over another model developed on the same dataset. Therefore, the AICc can estimate the relative quality between statistical models computed on the same dataset, but does not give any information about the absolute quality of the model. As a result, AICc thresholds indicating the absolute quality of a model cannot be found in the literature. However, considering each dataset separately, the lower the AICc value, the better the model. The AICc of each ordinal logistic regression model is used as the third and last indicator of the accuracy of discomfort glare prediction to compare the 63 evalglare options.

In contrast to Spearman and AUC statistical approaches, there exists no significance test to statistically compare the AICc of two ordinal logistic regression models. But, several thresholds of the difference between the AICc of two models that were computed from the same dataset have been published in the literature [28–31]. For this study, a threshold of 10 points, namely a difference of 10 points between the AICc values of two models, was used to determine that the model with the lower AICc value is significantly better than the other one. If the difference between the AICc values of two models that were computed from the same dataset is larger or equal to 10, the significant difference score between these two models is given one point. The significance of the difference between two evalglare options is evaluated on a score from 0 to 5 for each dataset, since the AICc difference test is done for each of the five discomfort glare indices.

4. Results and Discussion

In this section, the results of the study are presented and discussed. First, the three evalglare methods are compared, followed by the comparison of the two background luminance definitions, the three search radius, and the three task area sizes. At last, the use or not of the smooth parameter is investigated as well. Six graphs are used for each comparison: on the left, three graphs related to the field study, and on the right, three graphs related to the laboratory study. From top to bottom, the first graph uses the results of the first statistical approach, namely the Spearman correlation; the second graph uses the results of the second statistical approach, namely the AUC of the binary logistic regression models; and, the third graph uses the results of the third statistical approach, namely the AICc of the ordinal logistic regression models. The statistical results—Spearman correlation and logistic regressions—that were found to be non-significant with Bonferroni correction are still included in the graphs, but they can be recognized by graphical means. The datapoints based on the DGP index were removed from the boxplot graphs. The DGP model is indeed partly based on the vertical illuminance, which does not depend on detected glare sources. These datapoints tend therefore to remain stable throughout the different evalglare options and prevent us from drawing observations from the graphs. However, these datapoints are still plotted in the boxplot graphs as small orange triangle points. Finally, tables summarize for each comparison the total significant difference scores, which are the weighted sum of the significant difference scores of the three statistical approaches (Equation (1)):

$$S_{SD} = \frac{1}{3} * \frac{S_{SD,Spearman}}{50} + \frac{1}{3} * \frac{S_{SD,AUC}}{15} + \frac{1}{3} * \frac{S_{SD,AICc}}{5} \quad (1)$$

with S_{SD}, the total significant difference score;
$S_{SD,Spearman}$, the significant difference score from the Spearman statistical approach;
$S_{SD,AUC}$, the significant difference score from the AUC statistical approach; and,
$S_{SD,AICc}$, the significant difference score from the AICc statistical approach.

4.1. Evalglare Methods

In Figures 4–9, the indicators of accuracy of discomfort glare prediction are compared between the 11 different evalglare methods used in this study—factor method with factor 5, 6, 7, and 8; threshold method with threshold 1000, 2000, and 4000; task area method with factor 3, 4, 5, and 6. All other parameters (background luminance definition, search radius, task area size, and smooth option) are set to their default value, so that the methods can be compared on a neutral basis. This comparison is done for each of the five discomfort glare indices (DGP, DGI, CGI, DGImod, UGP), and for both the field (left) and laboratory (right) studies. Non-significant statistics (Spearman correlation and logistic regressions) are included in the graphs but are plotted as dimmed dots. The methods are classified along the X-axis in an ascending order of performance, in such a way that the best performing method can be easily recognized on the right.

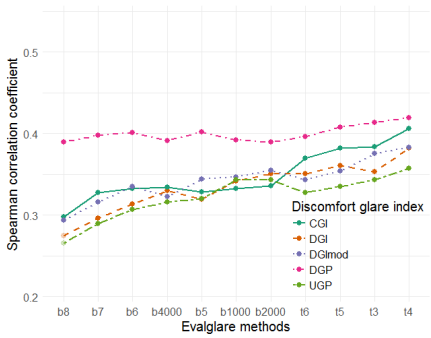


Figure 4. Comparison of Spearman rho for each discomfort glare index between the studied evalglare methods (field study).

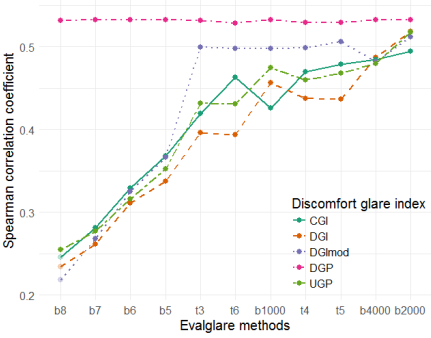


Figure 5. Comparison of Spearman rho for each discomfort glare index between the studied evalglare methods (laboratory study).

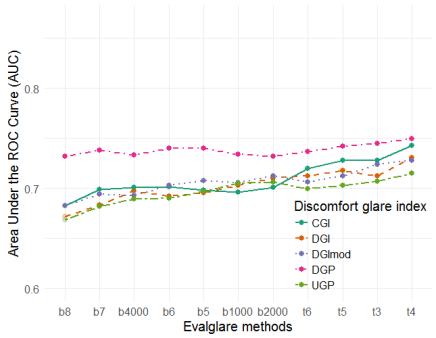


Figure 6. Comparison of Area Under the Curve (AUC) for each discomfort glare index between the studied evalglare methods (field study).

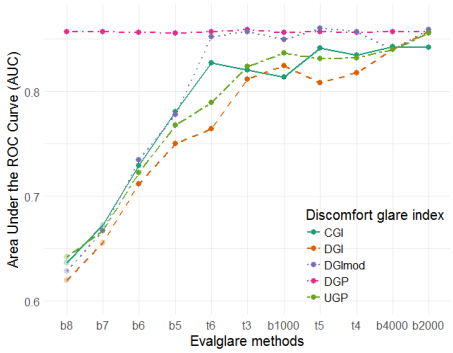


Figure 7. Comparison of AUC for each discomfort glare index between the studied evalglare methods (laboratory study).

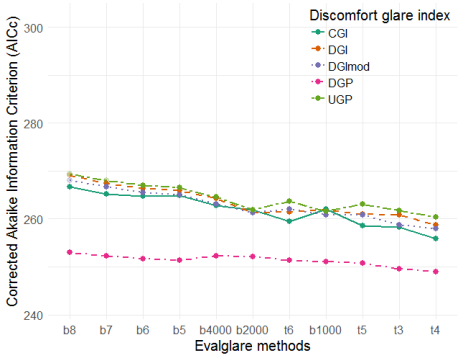


Figure 8. Comparison of Akaike's Information Criterion (AICc) for each discomfort glare index between the studied evalglare methods (field study).

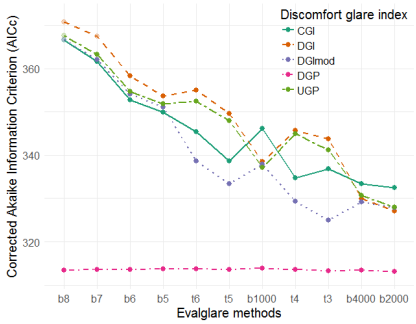


Figure 9. Comparison of AICc for each discomfort glare index between the studied evalglare methods (laboratory study).

From the graphs (Figures 4–9), it appears that the task area method seems to be more appropriate for the field study, and the threshold method for the laboratory study. The task area used with a factor 4 (t4) and the threshold of 2000 cd/m^2 (b2000) are the methods providing the best accuracy of discomfort glare prediction throughout the three different statistical approaches. In the graphs, the non-significant statistics—Spearman correlation coefficients or logistic regression models—are identifiable as the transparent points. Only a few appear to be non-significant, and these are only found in the factor method. For both studies, the factor methods (b5, b6, b7, b8) are the ones that are producing the worst discomfort glare prediction. In addition, the differences between the methods are more pronounced for the laboratory study than for the field study. This is probably partly due to the noise inherent to field studies data.

As observed in Tables 4 and 5, the significant difference scores do not exceed 82%. This is due to the fact that the difference between two evalglare options used to derive the DGP will almost never be large and significant, since this index was designed to be robust against variations of glare source detection methods. Therefore, a score of 80% means that for all other discomfort glare indices and for each significance test applied, the difference between the evalglare methods were significant. As already observed from the graphs, the differences are larger in the case of the laboratory study. The scores of the laboratory study support the hypothesis that the differences between the factor methods and the other methods are statistically significant, with the discomfort glare prediction becoming worse as the factor of the factor method is increased.

From these results, it is clear that the factor methods should be avoided. These methods provide inappropriate glare source detections, which result in inaccurate discomfort glare predictions. Why these methods fail to accurately detect glare sources could be answered by the following explanation.

Table 4. Significant difference scores (%) between each tested method (field study).

	b5	**b6**	**b7**	**b8**	**b1000**	**b2000**	**b4000**	**t3**	**t4**	**t5**
t6	2	0	10	36	0	0	0	0	15	6
t5	11	0	16	40	13	0	0	2	2	
t4	24	28	40	79	19	13	7	0		
t3	0	0	0	27	0	0	0			
b4000	0	0	0	0	0	2				
b2000	0	2	22	33	0					
b1000	0	0	7	27						
b8	26	43	44							
b7	2	6								
b6	2									

Table 5. Significant difference scores (%) between each tested method (laboratory study).

	b5	**b6**	**b7**	**b8**	**b1000**	**b2000**	**b4000**	**t3**	**t4**	**t5**
t6	20	33	71	80	16	42	20	20	11	27
t5	38	60	80	80	13	20	13	0	0	
t4	27	67	80	80	7	20	13	7		
t3	33	60	67	80	7	29	13			
b4000	82	80	80	80	7	0				
b2000	80	80	80	80	20					
b1000	38	62	80	80						
b8	80	73	7							
b7	73	22								
b6	24									

For dim light scenes, the glare source detection threshold while using a factor method will be generally quite low, since the average luminance of the scene is low. This will often result in an over-detection of glare sources. Figure 10 shows an example of a visual scene in which the computer screen was treated as a glare source by evalglare and factor 5 method, although the visual scene was ranked as "No discomfort" by the subject.



Figure 10. Glare source detection by evalglare factor 5 method for a visual scene of the field study.

On the opposite, when a scene is bright, the factor method will often fail to find glare sources (under-detection). Since the average luminance of the scene is relatively high, the glare source detection threshold will be high as well. Evalglare will thus miss some glare sources. The visual scene in Figure 11 was rated as "Disturbing", although no substantial glare sources were detected by evaglare and factor 7 method.

From the results, it can also be inferred that the choice of an evalglare method can be done according to the type of discomfort glare that is the most probable to occur in the studied visual scene. It appears that the task area method would be the most appropriate for visual scenes, in which contrast glare is likely to occur. On the other hand, the threshold method offers some advantages when being used for visual scenes with saturation glare, although the task area method delivers results in a similar range. This observation was expected and can be explained.

In the case of contrast glare, i.e., in the case of low vertical illuminance scenes, like in the field study, the task area method would be more appropriate since the adaptation level of the subject's eyes plays an important role in the determination of the glare source luminance level at which glare is perceived. The task area method includes the adaptation level in the glare source detection process, by using a task area as reference for the eyes adaptation level.



Figure 11. Glare source detection by evalglare factor 7 method for a visual scene of the laboratory study.

On the other hand, for saturation glare, which occurs in scenes with relatively high vertical illuminance, like in the laboratory study, the determination of the glare source luminance threshold does not directly depend on the adaptation of the subject's eyes. Therefore, an absolute threshold would offer better results for saturation glare detection. Up to now, the most common threshold value has been 2000 cd/m^2, and this value is supported by this study.

4.2. Background Luminance Definition

Figures 12–17 compare the two background luminance definitions by using boxplots for both the field (left) and laboratory (right) studies, of the three indicators of accuracy of discomfort glare prediction. More specifically, each boxplot is based on a group of 44 datapoints, with each one being an indicator corresponding to one of the four discomfort glare indices (DGP is left out of the boxplots) and one of the 11 evalglare methods (b5, b6, b7, b8, b1000, b2000, b4000, t3, t4, t5, t6). Non-significant statistics (Spearman correlation and logistic regressions) are included in the boxplots but are plotted as empty grey dots. The orange triangle points represent the indicators based on the DGP index. At last, the lines connecting two adjacent boxplots represent the evolution of an indicator when the background luminance definition is varied. If the lines would cross each other, then the influence of the background luminance definition would depend on the evalglare method or on the discomfort glare index used. Since the lines are not crossing much in this case, the influence of the background luminance definition is constant, whatever the evalglare method or the discomfort glare index is.

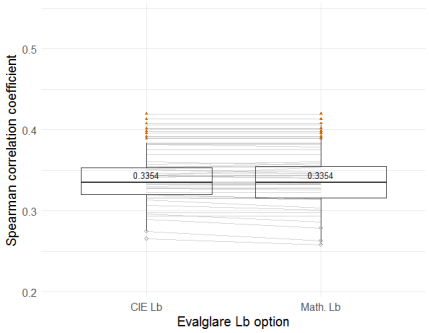


Figure 12. Boxplots of Spearman rho for the two background luminance definitions (field study).

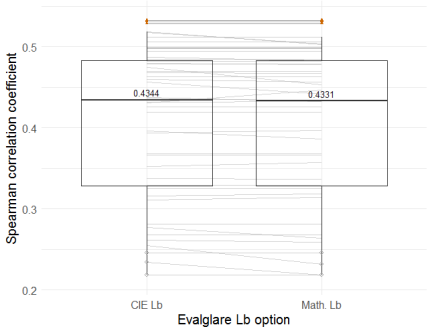


Figure 13. Boxplots of Spearman rho for the two background luminance definitions (laboratory study).

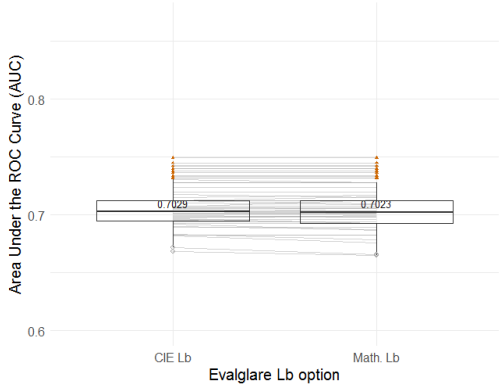


Figure 14. Boxplots of AUC for the two background luminance definitions (field study).

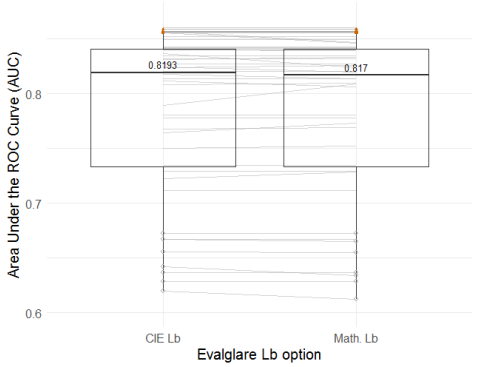


Figure 15. Boxplots of AUC for the two background luminance definitions (laboratory study).

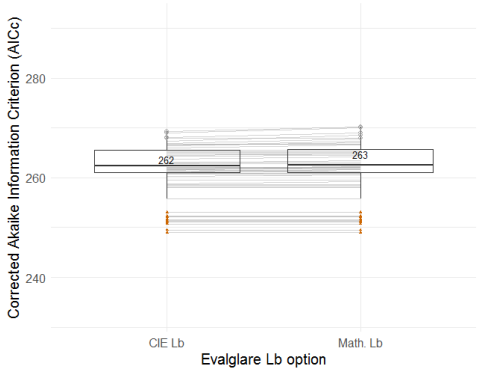


Figure 16. Boxplots of AICc for the two background luminance definitions (field study).

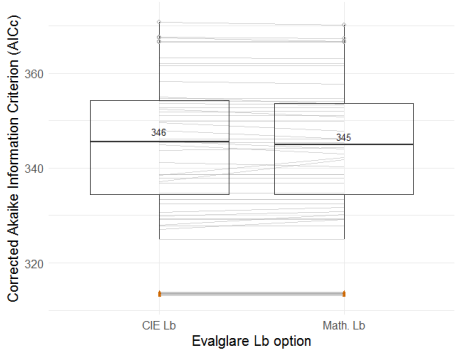


Figure 17. Boxplots of AICc for the two background luminance definitions (laboratory study).

In each figure (Figures 12–17), the overall accuracy of discomfort glare prediction can be compared between the use of the CIE definition of the background luminance and its mathematical definition. The difference between the two background luminance definitions lies in the fact that the CIE definition takes into account the cosine correction (Lambert's cosine law) in the computation of the background luminance. But, it seems that this difference does not show in the accuracy of discomfort glare prediction: the boxplots are similar for the field and laboratory studies and for each statistical approach. On another note, the boxplots of the laboratory study are more spread than those of the field study. Therefore, the variation in the accuracy of discomfort glare prediction between the evalglare methods or between the discomfort glare indices are larger for the laboratory study, as it was already observed in Figures 4–9.

Significance tests looking at the difference between the two background luminance definitions support the observations that are made according to the boxplots. The significant difference scores (Tables 6 and 7) do not exceed 13%, and are mainly 0%. This illustrates that the difference between the two definitions is almost never significant, depending on which significance test is applied. This is confirmed by looking more closely to the boxplots that are related to the AICc indicator: the variation in the AICc values between the use of the CIE definition or the mathematical definition is never larger than 10 points.

Table 6. Significant difference scores (%) between the two background luminance definitions (field study).

	b5	b6	b7	b8	b1000	b2000	b4000	t3	t4	t5	t6
CIE Lb >< Math. Lb	0	0	6	6	0	0	2	2	0	0	0

Table 7. Significant difference scores (%) between the two background luminance definitions (lab. study).

	b5	b6	b7	b8	b1000	b2000	b4000	t3	t4	t5	t6
CIE Lb >< Math. Lb	0	0	0	9	13	12	0	0	0	0	0

From these observations, it appears that there is no significant difference in the accuracy of discomfort glare prediction between the use of the CIE definition and the mathematical definition of the background luminance. Both could be used alternatively without observing any change in the results of a study. However, the influence of the background luminance definition, namely the influence of the use of the cosine correction in the background luminance computation, should be checked in the case of extreme visual scenes. Indeed, this parameter could have an influence when the luminance distribution of the background of a visual scene is extremely heterogeneous, for instance, when background luminance values are much higher—but is still not considered as a glare source—in one specific part of the field of view.

4.3. Search Radius

Figures 18–23 show boxplots that are built on the same principals than those in Figures 12–17, but in this case, the evalglare parameter being varied is the search radius. In each figure (Figures 18–23), the overall accuracy of discomfort glare prediction can be compared between the use of a search radius having an opening angle of 0.06, 0.2, or 0.3 radians. By varying the search radius, the maximal distance within which two nearby glaring pixels are merged in one glare source is varied. Therefore, the smaller the search radius, the smaller the solid angle of the detected glare sources but the more of them.

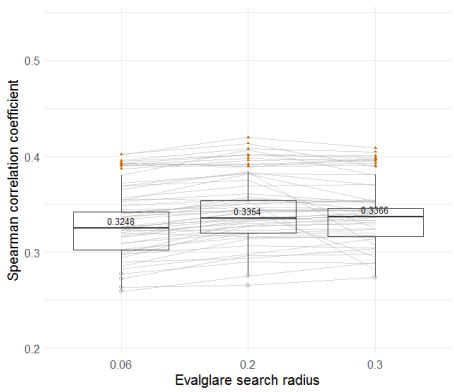


Figure 18. Boxplots of Spearman rho for the three search radius (field study).

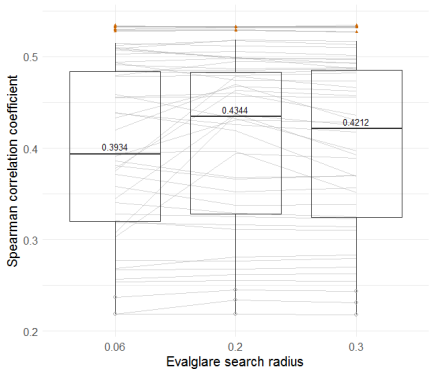


Figure 19. Boxplots of Spearman rho for the three search radius (laboratory study).

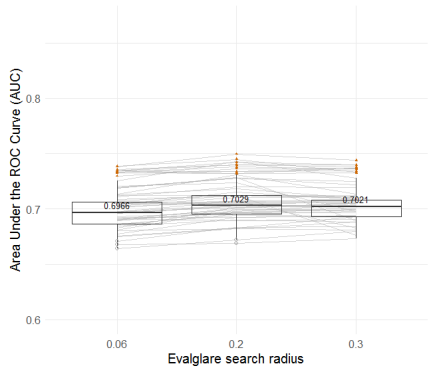


Figure 20. Boxplots of AUC for the three search radius (field study).

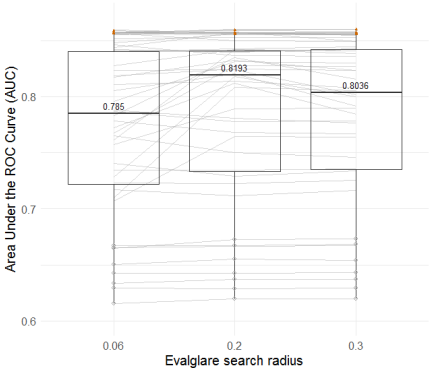


Figure 21. Boxplots of AUC for the three search radius (laboratory study).

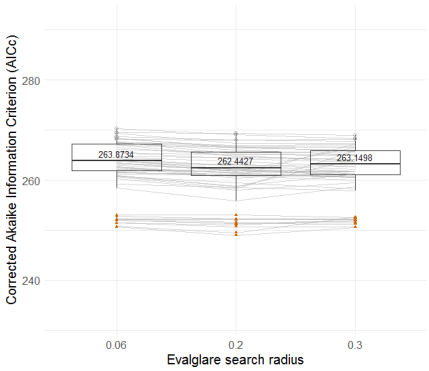


Figure 22. Boxplots of AICc for the three search radius (field study).

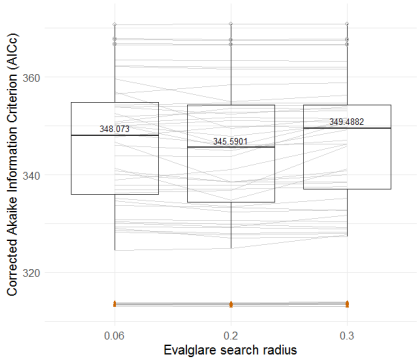


Figure 23. Boxplots of AICc for the three search radius (laboratory study).

The default search radius in evalglare is 0.2 radians, and it appears from the boxplots that this default parameter is appropriate. It is the one providing the best accuracy of discomfort glare prediction in the field and laboratory studies. However, several lines are crossing, especially in the laboratory study, as some lines go up while others go down when varying the search radius. This is a sign that the influence of the search radius is not constant.

Looking at the significant difference scores between the three search radius parameters (Tables 8 and 9), it appears that this parameter does not produce significant differences on the accuracy of discomfort glare prediction, at least not for the factor and threshold methods. When using the task area method, the differences might be interpreted as statistically significant in some cases. These cases correspond to the lines with the steepest slopes in the boxplot graphs.

Table 8. Significant difference scores (%) between the three search radius (field study).

	b5	**b6**	**b7**	**b8**	**b1000**	**b2000**	**b4000**	**t3**	**t4**	**t5**	**t6**
r0.2 >< r0.06	0	12	7	0	0	2	10	2	2	2	2
r0.2 >< r0.3	2	0	0	0	0	0	0	62	22	0	0
r0.06 >< r0.3	0	13	7	11	0	0	13	20	0	0	0

Table 9. Significant difference scores (%) between the three search radius (laboratory study).

	b5	b6	b7	b8	b1000	b2000	b4000	t3	t4	t5	t6
r0.2 >< r0.06	13	0	4	0	6	4	0	15	27	40	40
r0.2 >< r0.3	0	0	6	0	0	0	0	18	24	0	0
r0.06 >< r0.3	15	0	2	0	6	0	0	16	9	33	40

Although the differences in the accuracy of glare prediction could not be demonstrated as being significant in a majority of cases, there seems to be a tendency towards a better accuracy of discomfort glare prediction when using the default search radius. However, using only three variations of the search radius is not enough to grasp the full extent of the influence of the search radius on glare source detection, and indirectly on the accuracy of discomfort glare prediction. Moreover, the influence of the search radius most probably depends on the visual scene, and especially on the distance between two contrasted glare pixels in a luminance map. In the case of this study, the observers from both datasets were sitting close to the façade, thus at a relatively close distance from the blinds. But, this might not be the case for large open-plan offices. If the observer is located further away from the blinds, the distance between the contrasted pixels of the blinds will vary in the luminance map, and the opening angle of the search radius will have to be varied in order to produce a similar result than if the observer was sitting close to the façade. An extended study on the appropriate search radius for glare source detection would be required to thoroughly understand the influence of this parameter. In the meantime, it seems reasonable to keep using the default evalglare search radius having an opening angle of 0.2 radians.

4.4. Task Area Size

Figures 24–29 show boxplots that are similar than the ones in Figures 12–23, for both the field (left) and laboratory (right) studies, and for the three indicators of accuracy of discomfort glare prediction. However, in the case of the task area size parameter, each boxplot is based on a group of 16 datapoints. The 16 datapoints are the indicators corresponding to the four discomfort glare indices (DGI, CGI, DGImod, and UGP) and the four task area methods (t3, t4, t5, t6). The factor and threshold methods are left out of the boxplots since the variation due to the task area size has no influence on their accuracy of discomfort glare prediction. As the few non-significant statistics (Spearman correlation and logistic regressions) are found when using the factor method, all of the datapoints plotted in Figures 24–29 are based on significant statistics. At last, the orange triangle points represent the indicators based on the DGP index.

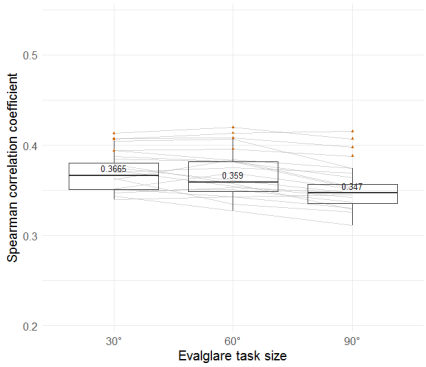


Figure 24. Boxplots of Spearman rho for the three task area sizes (field study).

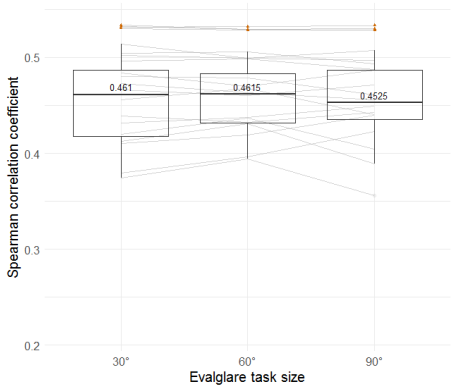


Figure 25. Boxplots of Spearman rho for the three task area sizes (laboratory study).

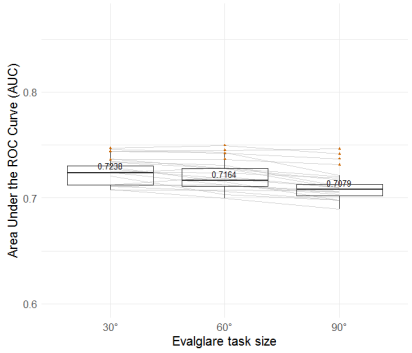


Figure 26. Boxplots of AUC for the three task area sizes (field study).

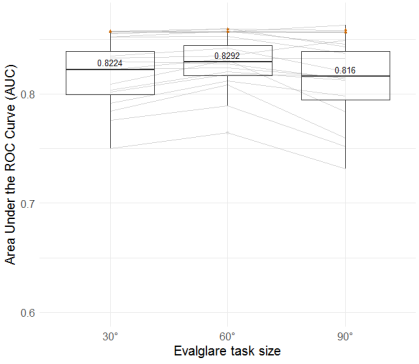


Figure 27. Boxplots of AUC for the three task area sizes (laboratory study).

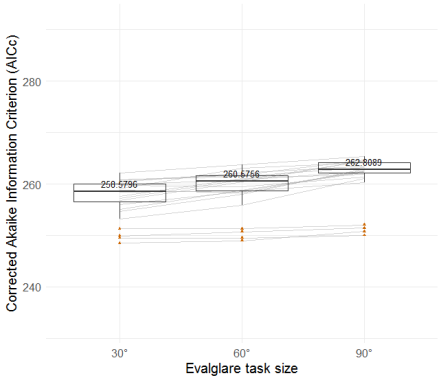


Figure 28. Boxplots of AICc for the three task area sizes (field study).

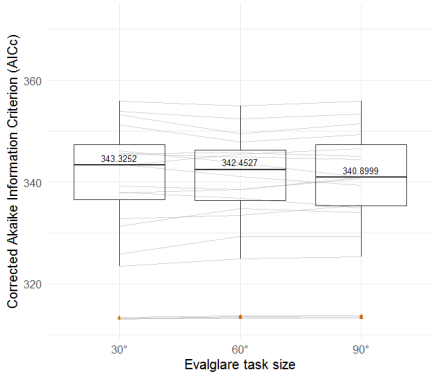


Figure 29. Boxplots of AICc for the three task area sizes (laboratory study).

The overall accuracy of discomfort glare prediction can be compared on the boxplots between the three different task area sizes, having, respectively, an opening angle of 30° (0.52 rad.), 60° (1 rad.), and 90° (1.57 rad.). The 60° task area opening angle is what is believed to be commonly used in evalglare, as this corresponds to the ergorama. Varying the task area size might be interpreted as varying the size of the part of the field of view to which the subject's eyes are adapting. But, increasing this task area size does not systematically mean increasing the average luminance of this task area; the visual scene will be determinant in this case. Figures 30 and 31 help to understand the implication of varying the task area size on the average task luminance, and thus on the glare source detection threshold. For the laboratory study (Figure 31), the variation of the task area size has a small and relatively constant impact on the task luminance: the larger the task area size, the larger the task luminance. In the case of the field study (Figure 30), the impact of the variation of the task area size on the task luminance is larger, but more chaotic. This is due to the fact that, in real office settings, the field of view changes a lot from one desk to the other, hence the luminance distribution of this field of view varies a lot as well. In a laboratory setting, on the contrary, the visual field is relatively constant, causing the variation in the task luminance to be relatively constant as well.

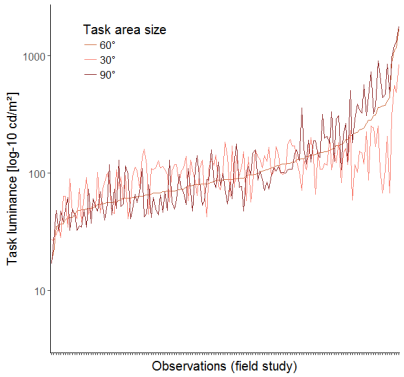


Figure 30. Comparison of the task area average luminance between the three different task area sizes for all glare evaluations of the field study.

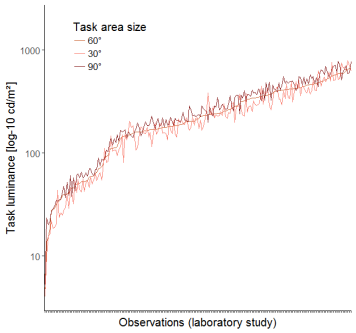


Figure 31. Comparison of the task area average luminance between the 3 different task area sizes for all glare evaluations of the lab study.

However, it seems that a consistent variation of the glare source detection threshold—due to a consistent variation of the task luminance—does not produce a consistent influence on the accuracy of discomfort glare prediction. In the boxplots of the laboratory study (Figures 25, 27 and 29), the lines are crossing and going in opposite directions, which means that the influence of the task area size is not consistent throughout the discomfort glare indices or the task area methods. Moreover, the three indicators of the accuracy of discomfort glare prediction disagree on which would be the best task area size. At last, the significant difference scores between the three task area sizes for the laboratory study (Table 10) are low or equal to 0%. No conclusions can therefore be drawn from the analysis of the task area size influence while using the laboratory dataset.

Table 10. Significant difference scores (%) between the three task area sizes (laboratory study).

	t3	t4	t5	t6
60° X 30°	0	6	6	0
60° X 90°	2	0	24	13
30° X 90°	0	0	0	0

On the other hand, from the boxplots of the field study (Figures 24, 26 and 28), a steady trend can be observed: by decreasing the task area size, the accuracy of discomfort glare prediction is increased. It is however quite difficult to explain this trend. What could be observed in Figure 30 is that when the task luminance is relatively low, using a smaller task area size tends to increase this task luminance; but when the task luminance is relatively high, using a smaller task area size tends to decrease the task luminance. A small task area size thus leads to a more constant task luminance throughout different visual scenes. A more accurate discomfort glare prediction could therefore be achieved thanks to the use of a less fluctuating eye adaptation level. In reality, it is indeed expected that the subject's eyes adapt to the computer screen brightness, which should not vary a lot. However, the differences between the three task area sizes do not appear to be statistically significant, even for the field study (Table 11). More insight on the actual task area, namely the area of the field of view to which the subject's eyes are really adapting, are required to better understand what can be seen here, and to determine an appropriate task area size.

Table 11. Significant difference scores (%) between the three task area sizes (field study).

	t3	t4	t5	t6
60° X 30°	0	0	0	0
60° X 90°	0	16	0	26
30° X 90°	0	0	2	10

4.5. Smooth Option

Figures 32–37 compare the accuracy of discomfort glare prediction when the detected glare sources are smoothed or not. Using the smooth parameter causes the pixels that are not detected as glaring pixels by the algorithm, but that are nested inside an area of glaring pixels to be considered as glaring pixels as well and included in the surrounding glare source. Therefore, when the smooth parameter is applied, a detected glare source in a luminance map will have a larger solid angle, but a lower average luminance. The smooth parameter is presumably seldom used, mainly because it did not belong to the recommended options in evalglare, and little data have been published about it, making its contribution not well understood. In addition, its computation time is three to four times longer.

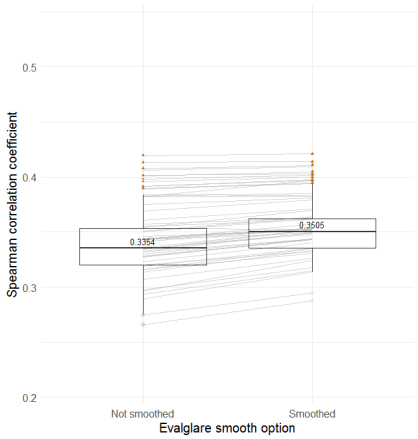


Figure 32. Boxplots of Spearman rho for the non-smooth/smooth parameter (field study).

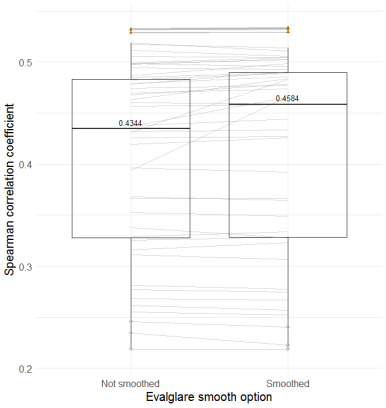


Figure 33. Boxplots of Spearman rho for the non-smooth/smooth parameter (laboratory study).

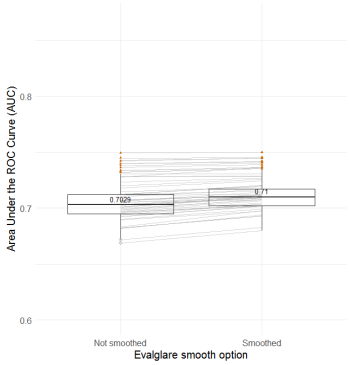


Figure 34. Boxplots of AUC for the non-smooth/smooth parameter (field study).

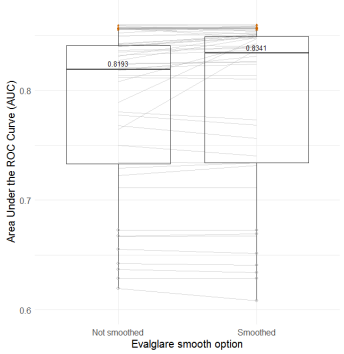


Figure 35. Boxplots of AUC for the non-smooth/smooth parameter (laboratory study).

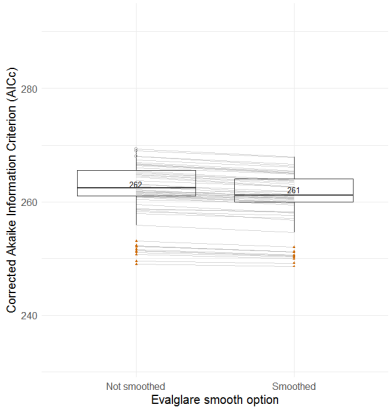


Figure 36. Boxplots of AICc for the non-smooth/smooth parameter (field study).

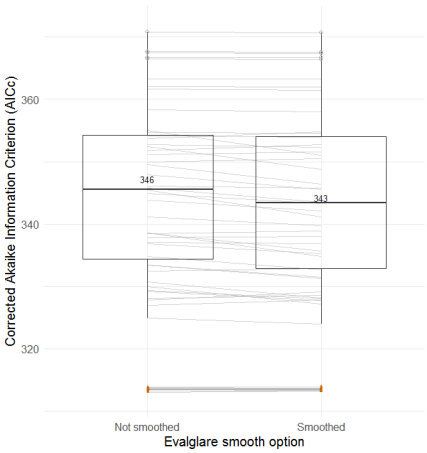


Figure 37. Boxplots of AICc for the non-smooth/smooth parameter (laboratory study).

From the boxplots (Figures 32–37), a general trend is observed towards a higher accuracy of discomfort glare prediction with the smooth parameter. This is especially visible for the field study, as the lines all go in the same direction. This implies that the influence of the smooth option is not dependent on the discomfort glare index that is used or the evalglare method applied. To understand why the smooth parameter offers a constant improvement of discomfort glare prediction, its impact on the four main physical quantities influencing discomfort glare [1] was investigated through the Glare Impact (GI). The GI was first introduced by [32], and it was redefined here, according to Equation (2).

$$\mathrm{GI} = \sum \frac{L_{s,i}^2 * \omega_i}{L_b * P_i^2} \tag{2}$$

with $L_{s,i}$, the luminance of the glare source;

ω_i, the solid angle of the glare source;
L_b, the luminance of the background; and,
P_i, the position index related to the glare source.

First, the variation of the GI according to the smooth parameter was studied. This did not help understanding the influence of the smooth parameter, since the variations of the GI due to the smoothing were not constant and very dependent on the visual scene. In bright visual scenes, a squared decrease in the average glare source luminance due to the use of the smooth parameter was generally balanced by the increase in the solid angle of this glare source. However, in low-light scenes, the squared decrease in the glare source luminance could most of the time not be entirely balanced by the increase in the solid angle. The only constant variation that is brought by the smooth parameter is the decrease in background luminance, as can be seen in Figures 38 and 39. Since the originally non-glaring pixels located next to a glare source are included in this glare source due to the smoothing, the average background luminance is lowered as some of the brightest pixels of the background—those located next to a glare source—are retrieved from this background. The constant decrease in the background luminance due to the smoothing could thus be linked to the constant increase in the accuracy of discomfort glare perception.

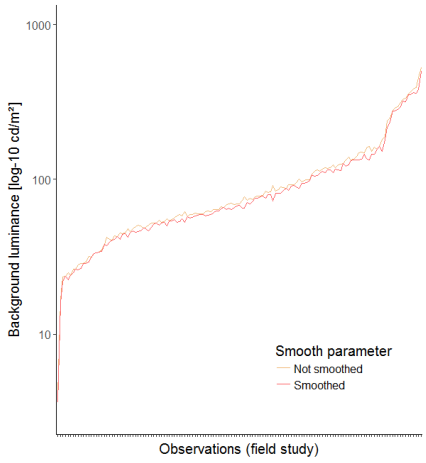


Figure 38. Comparison of the background luminance while varying the smooth parameter with the t4 method (task area method with a factor 4), for all glare evaluations of the field study.

Looking at the significant difference scores between the smooth/non-smooth parameter (Tables 12 and 13), the differences in the accuracy of discomfort glare prediction can be considered to be statistically significant only for a few cases, especially in the field study. The smooth parameter appears not to produce a strong significant difference in the accuracy of discomfort glare prediction, despite a clear tendency towards a better glare prediction with the smooth parameter applied (Figures 32–37).

Table 12. Significant difference scores (%) between the smooth/non-smooth parameter (field study).

	b5	**b6**	**b7**	**b8**	**b1000**	**b2000**	**b4000**	**t3**	**t4**	**t5**	**t6**
Smooth >< Non-smooth	12	24	44	49	2	16	31	0	0	27	29

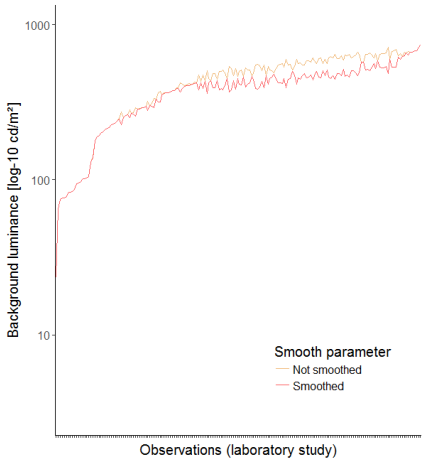


Figure 39. Comparison of the background luminance while varying the smooth parameter with the b2000 method (method with a threshold of 2000 cd/m^2), for all glare evaluations of the laboratory study.

Table 13. Significant difference scores (%) between the smooth/non-smooth parameter (laboratory study).

	b5	b6	b7	b8	b1000	b2000	b4000	t3	t4	t5	t6
Smooth >< Non-smooth	0	0	0	0	0	0	19	0	0	7	35

The observations that are made here following the investigation of the smooth parameter should not lead to an excessive and indiscriminate use of this parameter, with the sole purpose to improve the correlation between the subjective glare ratings and the discomfort glare indices in a study. These results should first be validated in an extended study. Moreover, the settings choice in evalglare should always be done in an objective and sensible way, so as not to bias the results.

At last, the results that are presented here should be interpreted with respect to the limitations of the study. This study concentrated on the most common settings that are available in evalglare. However, other settings—such as the definition of the position index—might also influence the accuracy of discomfort glare prediction. Moreover, the observations are made based on a limited number of visual scenes. It is believed that the use of two different datasets brings a larger diversity in the studied visual scenes and their luminance distributions, making the results applicable to a large number of situations. But, different or extreme visual scenes could produce different results. Finally, these results are based on the five most common discomfort glare indices for daylighting. However, these indices are not performing as well as could be expected [33], and a lot of research is still going on to understand the mechanism behind discomfort glare perception and to determine an accurate way of measuring it. Moreover, one of these five indices, the DGP, possesses a validity range, which means that DGP values lower than 0.2 or higher than 0.8 should be interpreted with an additional layer of caution.

5. Conclusions

In this study, the influence of the choice of evalglare methods and parameters on the accuracy of discomfort glare prediction was investigated. The aim was to determine which method and parameters offer the best discomfort glare prediction for both types of discomfort glare, namely the contrast and

saturation glare. Therefore, two datasets were used in this study, each one representative of one type of glare. In total, 63 different evalglare options were tested (Table 2), and for each option, five common daylight discomfort glare indices were calculated (DGP, DGI, CGI, DGImod, and UGP). Three statistical indicators were computed for each index, for each evalglare option, and for both datasets, so that the accuracy of discomfort glare prediction deriving from each evalglare option can be evaluated. These three statistical indicators are the Spearman correlation coefficient (or Spearman rho), the Area Under the ROC Curve of a binomial logistic regression model (or AUC), and the corrected Akaike's Information Criterion of an ordinal logistic regression model (or AICc).

The results confirmed that the task area method should be preferred when evaluating visual scenes with contrast glare. For visual scenes where saturation glare is more predominant, the threshold method seems the most appropriate one, although the task area method offers very similar results. More specifically, the results showed that the task area method should be applied with a multiplying factor of 4 or 5, while the most appropriate threshold for the threshold method seems to be 2000 cd/m^2, as is generally found in the literature. The calculation method of the background luminance—CIE definition or mathematical definition—seems to have no influence on the accuracy of discomfort prediction. A small trend could be observed for the influence of the search radius and the task area size parameter, although their influence on the accuracy of discomfort glare prediction could not be demonstrated as being statistically significant. The default search radius in evalglare, having an opening angle of 0.2 radians, was the one leading to the best discomfort glare prediction. As for the task area size, it seems that a smaller task area size, having an opening angle between 30° and 60°, would be more appropriate for discomfort glare prediction. However, more research involving datasets with different visual conditions is required to confirm these results. At last and quite surprisingly, applying the smooth parameter appeared to generate a more accurate discomfort glare prediction. It was hypothesized that this effect might be due to the decrease in background luminance when applying the smoothing. Rather than resulting in an unreasonable use of the smooth parameter to improve discomfort glare studies results, this observation should initiate the reconsideration of the basis of most discomfort glare indices nowadays, namely the Glare Impact formula (Equation (2)). Since it was observed that, for both studies, the accuracy of discomfort glare prediction was most certainly improved by decreasing the background luminance, the weighting or even the use of this physical quantity in discomfort glare models could be questioned. An extended laboratory study reassessing the influence of each one of the four main variables that is used in discomfort glare models (Ls, ω, Lb, and P) would be required, to validate the basis of the discomfort glare knowledge and to provide a clear definition of a glare source.

In addition, the authors would like to emphasize the importance of the choice of evalglare methods and parameters. When using evalglare, one should always be aware that this tool could lead to very different results in discomfort glare index calculation depending on these choices. Figures 40 and 41 show extreme examples of such variations in discomfort glare indices values that were observed in the framework of this study. Although the DGP was found to be only slightly influenced by the detection parameters and methods in evalglare, the settings could matter as well for specific cases. In Figure 40, an extreme visual scene from each dataset would change from the "disturbing glare" category to the "intolerable glare" category (thresholds defined according to [34]) due to the use of different settings in evalglare. More extreme variations were observed for the four other discomfort glare indices (DGI, CGI, DGImod, and UGP) (Figure 41). In the given examples (Figures 42 and 43), no glare source was found by using the b1000_Lb method for the field study example (Figure 42, left) or the b7_Lb method for the laboratory study example (Figure 43, right). The value of the CGI index corresponding to these two scenes is 0, and they are therefore categorized as "Imperceptible glare" (Figure 41). But, for other settings, such as the t3_smoothed method for the field study example (Figure 42, right) and the b1000_r0.06 method for the laboratory study example (Figure 43, left), glare sources are detected in the scenes. The same scenes are then categorized as "Unacceptable glare" or even "Uncomfortable glare" (thresholds defined according to [17,35]) (Figure 41). It is therefore

strongly recommended to create a check file when using evalglare to calculate discomfort glare indices from a luminance map and examine visually the glare source(s) detected. The visual analysis of the glare sources is a useful way to verify that the glare sources detected are reasonable.

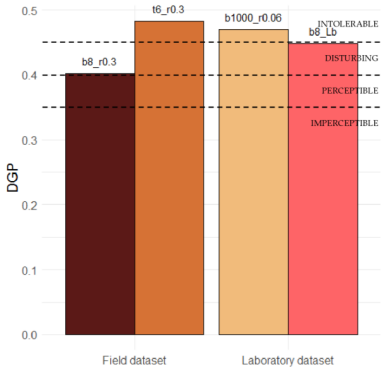


Figure 40. DGP of the same visual scene for different evalglare methods and parameters (field and laboratory studies).

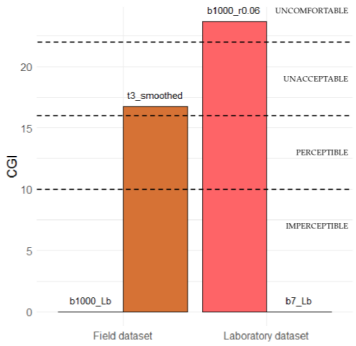


Figure 41. Commission on Illumination Glare Index (CGI) of the same visual scene for different evalglare methods and parameters (field and laboratory studies).

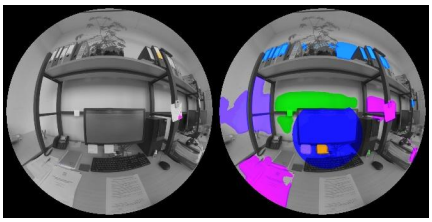


Figure 42. Extreme example (field study) of the difference in glare source(s) detection resulting from the b1000_Lb setting (**left**) and the t3_smoothed setting (**right**) in evalglare.

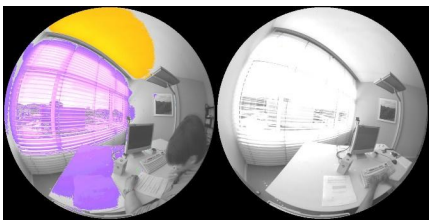


Figure 43. Extreme example (laboratory study) of the difference in glare source(s) detection resulting from the b1000_r0.06 setting (**left**) and the b7_Lb setting (**right**) in evalglare.

To conclude, for predominating saturation glare scenes, it would be beneficial to use an absolute threshold of 2000 cd/m^2. This method should also be preferred for simulation work with an observer location close to the façade. Using the task area method with a factor 4 or 5 delivers for all of the investigated cases (saturation and contrast glare scenes) reasonable results and it is the preferred option for predominating contrast glare scenes. This method should be applied in simulation work, when the observer is located further away from the façade, although the task area definition might be sensitive. Using the factor method—evalglare default method—was found to lead to significantly lower performances and is therefore not recommended. From this study, the influences of the background luminance definition, the search radius, and the task area size were found to be not statistically significant. It is therefore recommended to use the default setting for these parameters. Further research on the definition of a glare source in daylighting is required, so that these parameters can be determined knowingly and reliably.

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References

1. Commission Internationale de l'Eclairage (CIE). *Discomfort Glare in the Interior Working Environment*; Commission Internationale de l'Eclairage: Vienna, Austria, 1983; p. 52.
2. Pierson, C.; Wienold, J.; Bodart, M. Review of factors influencing perceived discomfort glare from daylighting. *J. Illum. Eng. Soc. N. Am.* **2018**, *14*, 111–148.
3. Wienold, J.; Christoffersen, J. Evaluation methods and development of a new glare prediction model for daylight environments with the use of ccd cameras. *Energy Build.* **2006**, *38*, 743–757. [CrossRef]
4. Wienold, J.; Reetz, C.; Kuhn, T.E.; Christoffersen, J. Evalglare—A new radiance-based tool to evaluate daylight glare in office spaces. In Proceedings of the 3rd International Radiance Workshop, Fribourg, Switzerland, 11–12 October 2004.
5. Wienold, J. New features of evalglare. In Proceedings of the 11th International Radiance Workshop, Copenhagen, Denmark, 12–14 September 2012.
6. Wienold, J.; Andersen, M. Evalglare 2.0–new features faster and more robust hdr-image evaluation. In Proceedings of the 15th International Radiance Workshop, Padua, Italy, 29–31 August 2016.
7. Wienold, J. Daylight Glare in Offices. Ph.D. Thesis, Universität Karlsruhe (TH), Freiburg, Germany, 2009.

8. Jakubiec, J.A.; Reinhart, C.F. Diva 2.0: Integrating daylight and thermal simulations using rhinoceros 3d and energyplus. In Proceedings of the Building Simulation 2011 12th Conference of International Building Performance Simulation Association, Sydney, Australia, 14–16 November 2011.
9. Pierson, C.; Piderit, M.B.; Wienold, J.; Bodart, M. Discomfort glare from daylighting: Influence of culture on discomfort glare perception. In Proceedings of the CIE 2017 Midterm Meeting, Jeju, Korea, 23–25 October 2017.
10. Moosmann, C.; Wienold, J.; Wagner, A.; Wittwer, V. AbschluErmittlung Relevanter Einflussgrößen auf Die Subjektive Bewertung von Tageslicht zur Bewertung des Visuellen Komforts in Büroräumen. Abschlussbericht. 2012. Available online: https://publikationen.bibliothek.kit.edu/1000034968 (accessed on 6 June 2018).
11. Dubois, M.-C. *Impact of Shading Devices on Daylight Quality in Office—Simulations with Radiance*; TABK–01/3062; Lund University: Lund, Sweden, 2001; p. 162.
12. Shin, J.Y.; Yun, G.Y.; Kim, J.T. View types and luminance effects on discomfort glare assessment from windows. *Energy Build.* **2012**, *46*, 139–145. [CrossRef]
13. Bülow-Hübe, H. *Daylight in Glazed Office Buildings—A Comparative Study of Daylight Availability, Luminance and Illuminance Distribution for an Office Room with Three Different Glass Areas*; EBD-R–08/17; Lund University: Lund, Sweden, 2008; p. 98.
14. Lee, E.S.; Clear, R.D.; Fernandes, L.; Ward, G. *Commissioning and Verification Procedures for the Automated Roller Shade System at the New York Times Headquarters, New York*; Lawrence Berkeley National Laboratory (LBNL): Berkeley, CA, USA, 2007; p. 112.
15. Van Den Wymelenberg, K.; Inanici, M.; Johnson, P. The effect of luminance distribution patterns on occupant preference in a daylit office environment. *J. Illum. Eng. Soc.* **2010**, *7*, 103–122.
16. Chauvel, P.; Collins, J.B.; Dogniaux, R.; Longmore, J. Glare from windows: Current views of the problem. *Light. Res. Technol.* **1982**, *14*, 31–46. [CrossRef]
17. Einhorn, H.D. Discomfort glare: A formula to bridge differences. *Light. Res. Technol.* **1979**, *11*, 90–94. [CrossRef]
18. Fisekis, K.; Davies, M.; Kolokotroni, M.; Langford, P. Prediction of discomfort glare from windows. *Light. Res. Technol.* **2003**, *35*, 360–371. [CrossRef]
19. Hirning, M.B.; Isoardi, G.L.; Cowling, I. Discomfort glare in open plan green buildings. *Energy Build.* **2014**, *70*, 427–440. [CrossRef]
20. Siegel, S. *Nonparametric Statistics for the Behavioral Sciences*; McGraw-Hill Book Company: New York, NY, USA, 1956.
21. Ferguson, C.J. An effect size primer: A guide for clinicians and researchers. *Prof. Psychol. Res. Pract.* **2009**, *40*, 532–538. [CrossRef]
22. Diedenhofen, B.; Musch, J. Cocor: A comprehensive solution for the statistical comparison of correlations. *PLoS ONE* **2015**, *10*, e0121945. [CrossRef] [PubMed]
23. Hosmer, D.W.; Lemeshow, S. *Applied Logistic Regression*, 2nd ed; Wiley: Toronto, ON, Canada, 2000.
24. Safari, S.; Baratloo, A.; Elfil, M.; Negida, A. Evidence based emergency medicine; part 5 receiver operating curve and area under the curve. *Emergency* **2016**, *4*, 111–113. [PubMed]
25. Venkatraman, E.S.; Begg, C.B. A distribution-free procedure for comparing receiver operating characteristic curves from a paired experiment. *Biometrika* **1996**, *83*, 835–848. [CrossRef]
26. DeLong, E.R.; DeLong, D.M.; Clarke-Pearson, D.L. Comparing the areas under two or more correlated receiver operating characteristic curves: A nonparametric approach. *Biometrics* **1988**, *44*, 837–845. [CrossRef] [PubMed]
27. Pepe, M.; Longton, G.; Janes, H. *Estimation and Comparison of Receiver Operating Characteristic Curves*; Biostatistics Working Paper Series; The Berkeley Electronic Press: Berkeley, CA, USA, 2008.
28. Murtaugh, P.A. In defense of *p* values. *Ecology* **2014**, *95*, 611–617. [CrossRef] [PubMed]
29. Burnham, K.P.; Anderson, D.R. *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach*, 2nd ed.; Springer-Verlag: New York, NY, USA, 2002.
30. Brewer, M.J.; Butler, A. *Model Selection and the Cult of Aic*; Universitat Autònoma de Barcelona: Barcelona, Spain, 2017.
31. Hurvich, C.M.; Tsai, C.-L. Regression and time series model selection in small samples. *Biometrika* **1989**, *76*, 297–307. [CrossRef]

32. Sarey Khanie, M.; Jia, Y.; Wienold, J.; Andersen, M. A sensitivity analysis on glare detection parameters. In Proceedings of the BS2015-14th International Conference of the International Building Performance Simulation Association, Hyderabad, India, 7–9 December 2015.
33. Suk, J.Y.; Schiler, M.; Kensek, K. Investigation of existing discomfort glare indices using human subject study data. *Build. Environ.* **2017**, *113*, 121–130. [CrossRef]
34. Reinhart, C.; Wienold, J. The daylighting dashboard—A simulation-based design analysis for daylit spaces. *Build. Environ.* **2011**, *46*, 386–396. [CrossRef]
35. Boyce, P.R. *Human Factors in Lighting*, 3rd ed.; Taylor & Francis Group: Boca Raton, FL, USA, 2014; p. 690.



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Appendix J

Journal Article Accepted in Leukos

The appended article is the accepted manuscript of a tutorial article accepted for publication in LEUKOS [Pierson et al. 2019a], reproduced with permission of the Illuminating Engineering Society.

Tutorial: Luminance Maps for Daylighting Studies from High Dynamic Range Photography

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In the field of lighting, luminance maps are often used to evaluate point-in-time lighting scenes from the occupant's vantage point. High Dynamic Range (HDR) photography can be used to generate such luminance maps. The aim of this tutorial is to present a comprehensive overview of a step-by-step procedure to generate a 180° luminance map of a daylit scene from a sequence of multiple exposures with semi-professional equipment and the Radiance suite of programs. The procedure consists of capturing a sequence of multiple exposures of the visual scene; in selecting the useful exposures; in merging the exposures to generate the HDR image by using the predefined camera response function; in nullifying the exposure value; in resizing and cropping the HDR image by using the predefined fisheye view coordinates; in adjusting the projection of the HDR image by using the predefined distortion function; in correcting the vignetting of the HDR image by using the predefined vignetting curves; in correcting the alterations of the HDR image due to the Neutral Density (ND) filter if one was used, by using the predefined ND correction function; in adjusting the photometry of the HDR image by using the measured spot luminance value; in editing the HDR image header by using the predefined projection type and real viewing angle; and in checking the validity of the HDR image by using the measured vertical illuminance, and, if needed, the predefined luminous range. To conclude, an analysis of errors is made and attention points to adapt the procedure for artificial or circadian lighting studies are discussed.

Keywords: High Dynamic Range (HDR); luminance map; calibration; daylighting; photography; light measurement

Learning Outcomes

It is our intent that, after studying this article, the reader will:

1. be able to explain the concept of HDR photography —why is it used, and what is the basic concept;
2. feel familiar with some basic concepts related to digital imaging and photography that are required to understand the calibration procedure: *no-parallax point*, *vignetting*, *camera response function*, *pixel overflow*, *lens flare*, *projection types*, *bracketing*, *image header*;
3. have an overview of the multiple steps required to create (i.e. generate and calibrate) a luminance map using affordable equipment and free software, and understand the reasons why each of these steps is necessary;
4. be able to generate an HDR image of a daylit visual scene, and calibrate it radiometrically, photometrically, and geometrically;

5. understand what is a reasonable range for each calibration feature, and for the luminance and vertical illuminance errors of a calibrated HDR image;
6. be aware of the limitations and pitfalls associated with the use of HDR photography for luminance measurement in daylighting, as well as the challenges when adapting the technique to electric lighting and color studies.

1. Introduction

In the field of lighting, luminance maps are often used to evaluate point-in-time lighting scenes from the occupant's vantage point. High Dynamic Range (HDR) photography can be used to generate such luminance maps. HDR photography consists of capturing multiple exposures of a scene from an identical vantage point and merging them in order to obtain an image with a higher range of brightness, namely an HDR image. In traditional images, also called Low Dynamic Range (LDR) images, the contrast ratio is limited by the pixel range and the response function of the camera. For instance, the camera used for the examples given in this tutorial can capture LDR images with a maximal contrast ratio of around 33:1. Though indoor daylit scenes can have a dynamic range up to 10^9:1 if the sun is in the field of view (FOV) (Jakubiec et al. 2016b). After calibration, a luminance map is produced from the HDR image, and can be used to derive much useful information such as the average luminance and glare source(s) in the FOV, or the vertical illuminance.

Nowadays, there exist two main methods of generating calibrated HDR images: absolute calibration and step-by-step calibration with an automatic merging algorithm. The absolute calibration consists of finding, for each exposure, a direct relationship between each pixel value and the luminance of the point it represents in the scene, with the relationship being applicable for all luminance levels that can be found in the field. From these relationships, the luminance validity range of each exposure can be defined, and the merging of multiple exposures into an HDR image is done accordingly (Dumortier et al. 2005). This method requires proper equipment and coding skills; hence it is principally used by professional manufacturers to produce luminance cameras. Due to the demanding calibration process required for high-precision solutions, luminance cameras tend to be expensive and often not commercially viable for lighting research (Wüller and Gabele 2007). The step-by-step calibration consists of applying an automatic algorithm that merges multiple exposures into an HDR image while doing a radiometric calibration, before manually adjusting the generated HDR image to calibrate it photometrically and geometrically. There exist several automatic merging algorithms such as *hdrgen* from *Radiance* (Ward 1993) or *pfscalibration* from *pfstools* (Mantiuk et al. 2007), although they are generally based on the same principle (see 2.4.3). This step-by-step calibration makes it possible to produce luminance maps with good photometric accuracy, but without requiring expensive equipment nor specific coding skill. Several studies (Cai and Chung 2011; Inanici 2006; Stanley 2016) have shown that, for scenes where the maximal luminance value was lower than 30,000 cd/m², most luminance values from the luminance map could be expected within a 10% error range, although higher errors also occurred. This error margin makes HDR photography relevant as a

measurement tool, but the step-by-step calibration is tedious and error-prone since it involves multiple steps.

The aim of this tutorial article is to present a synthetic overview of the step-by-step calibration process required to generate an HDR image that can be used to study the luminance distribution in an interior daylit scene, and to propose a practical procedure to execute it. The scope of this tutorial is restricted to the generation of luminance maps covering a 180° FOV from a sequence of jpeg images, and requires therefore the use of a 180° fisheye lens. However, the steps described in the tutorial can be adapted for the capture of a sequence of raw images or the use of a normal (non-fisheye) lens, on condition that this lens is not a zoom lens. Unless the zoom is fixed, it is not possible to ensure that the lens is in the exact same position during the entire calibration procedure and for all following captures of LDR sequences, which causes a reproducibility issue.

A thorough description of each step of the process is provided, as well as requirements, options, and common mistakes. Examples performed using the equipment described below are also presented in boxes at the end of some sections to give an idea of what should be expected as calibration features. References are made to useful literature, and attention points are given to adapt the method for artificial or circadian lighting studies.

2. Tutorial: luminance maps from HDR photography for daylighting research

1. Requirements

1. Software

This tutorial to generate calibrated HDR fisheye images is based on several freely accessible software, namely *qDslrDashboard* (Hubai 2014) to remotely control the camera, the *Radiance* suite of programs (Ward 1987) to process the images, and *Photosphere* (Ward 2001) to apply the photometric adjustment. It is recommended to use the latest official release of these software packages. Links to the software packages are given in the references.

For the examples given in this tutorial, version 3.5.5 of *qDslrDashboard* was installed, although a new version (3.5.7) has been released since then. Version 5.2 of *Radiance* was used, which includes the programs *falsecolor*, *hdrgen*, *ra_xyze*, *pcomb*, *pcompos*, *pfilt*, *ximage*, *getinfo*, and *evalglare*. Moreover, the latest version of *evalglare* (2.08) was used, although this version is not yet updated in *Radiance* 5.2. Version 1.8.21U of *Photosphere* was also used, although a new version (1.8.25U) has been released in the meantime.

2. Hardware

The following hardware equipment is required to generate calibrated HDR fisheye images in order to analyze daylit scenes. This equipment is needed each time a new calibrated HDR fisheye image has to be generated:

- a Digital Single-Lens Reflex (DSLR) camera (CCD and CMOS sensors are equivalent competitors in the camera market nowadays (Stanley 2016))
- a circular fisheye lens which is compatible with the camera (fisheye lenses are frequently used in lighting research to maximize the captured FOV)
- a tripod on which to set the camera to ensure that the camera does not move during the sequence of multiple exposures
- a computer to remotely control the camera and process the images
- a calibrated spot luminance meter and a middle gray target to make the photometric adjustment through a spot luminance measure on the target (L_T). In case of expected very high luminance (e.g. sun seen through fabric), it is useful to use a translucent target, which should be lit by the sun and placed on the window. Both gray and translucent targets should show near to lambertian behavior to limit the influence of changing luminance values under different viewing angles.
- a calibrated illuminance meter to check the validity of the calibrated HDR fisheye image
- a ND filter could be needed if the sun or a very bright surface is in the FOV

Some of the equipment, though, is only needed to conduct the one-time setup for a specific camera/lens association (see 2.3):

- a color chart
- a panoramic rotation unit and a sliding plate to move the camera on the tripod
- a stable and bright light source (e.g. a halogen spotlight) in a dark room, or a stable overcast sky simulator (e.g. a mirror box) with a semicircular platform

Before starting the step-by-step calibration, the proper functioning of the equipment should be ensured, especially regarding the camera and the lens.

Because it deteriorates over time, the camera sensor should be checked for stuck, dead, or hot pixels (Jacobs and Wilson 2007). Stuck pixels are damaged pixels that will always appear colored or overexposed, even if no light reaches the sensor. Therefore, by taking a picture with the lens cap on the camera, stuck pixels are detected as the colored or white spots in the image. Dead pixels are permanently damaged pixels that do not receive any power. They will thus always appear black, even when the image is fully overexposed. Hot pixels are not permanently damaged, but show up during long exposures as the sensor heats up. To detect hot pixels, a picture should be taken with the lens cap on using a long exposure. Every non-black and non-stuck pixel in that long-exposed image is a hot pixel. Hot pixels should not be a problem since for daylit scenes,

the maximal exposure time should be kept under 2 seconds to prevent the lighting conditions to vary too much. However, the presence of several stuck or dead pixels requires to change camera to avoid distorted measurements.

The reproducibility of the camera should be checked as well. This can be done easily in a stable indoor scene, under a non-flickering (see 3.2) light source. The camera is set on the tripod and remotely controlled by the computer to ensure immobility. An LDR image is captured for each pertinent lens aperture with all other settings fixed. Without changing the situation nor moving the camera, a second series of LDR images is captured for each previous aperture and the exact same settings. In an image editing software, the LDR images can be analyzed pixel by pixel. If non-black corresponding pixels in two LDR images of same aperture have the same RGB values, the images captured by the camera are reproducible. This test could also be conducted by varying the exposure time instead of the lens aperture.

For the examples given in this tutorial, the equipment that was used consists of a Canon EOS 5D Mark II camera and a Sigma EX DG 8mm f/3.5 fisheye lens. The camera is remotely controlled by a computer with *qDslrDashboard* via USB, and the images are processed with *Radiance* and *Photosphere*. The ND filter used in specific cases is a Kodak Wratten 3.0 ND filter. Furthermore, a Hagner digital luxmeter EC1-X and a Konica Minolta LS-110 luminance meter, both calibrated in the 12 months preceding the data acquisition, are used. The sensor of the camera was checked with the described methods and seems to be clear of stuck and dead pixels, but shows several hot pixels for an exposure time of 30 seconds. The camera also provides reproducible results.

3. Camera settings

The camera settings should be set according to Table 1, as it has been recommended in the literature (Inanici 2009; Reinhard et al. 2006). These settings have to be kept constant for the whole calibration process and every generated luminance maps afterwards. For instance, modifying the white balance setting during the process would alter the color space transitions (Inanici 2006) and the camera response function (Jacobs 2012), which would result in calibration errors. Also, the focus value, if not locked, could vary between each exposure, which would hinder the merging of these exposures.

Table 1. Camera settings that should be used to capture a sequence of multiple exposures for HDR photography.

Setting	Value
Film speed	ISO 100
White balance	Daylight (5200K)
Exposure mode	Manual
Light metering mode	Insignificant
Focus mode	Manual
Focus value	Infinite
Image quality	Largest
Image type	JPEG or RAW
Picture style	Neutral
Peripheral illumination correction	Disabled
Color space	sRGB

Some settings from Table 1 might be referenced differently when using another camera brand. However, it is important to make sure that all image effects or corrections applied by the camera are disabled or set to neutral. Regarding aperture and mean exposure time, these settings will be determined below (see 2.4.1) and are set through the remote control software.

2. Procedure

The complete procedure to create a 180° luminance map from a visual scene with daylight is shown in Figure 1. Each step of this procedure is explained in detail in this article (2.4 and 2.5), and the lines of code to execute the steps in *Radiance* are given. The procedure consists of capturing a sequence of multiple exposures of the visual scene; in selecting the useful exposures; in merging the exposures to generate the HDR image by using the predefined camera response function; in nullifying the exposure value; in resizing and cropping the HDR image by using the predefined fisheye view coordinates; in adjusting the projection of the HDR image by using the predefined distortion function; in correcting the vignetting of the HDR image by using the predefined vignetting curves; in correcting the alterations of the HDR image due to the ND filter if one was used, by using the predefined ND correction function; in adjusting the photometry of the HDR image by using the measured spot luminance value; in editing the HDR image header by using the predefined projection type and real viewing angle; and in checking the validity of the HDR image by using the measured vertical illuminance, and if needed the predefined luminous range.

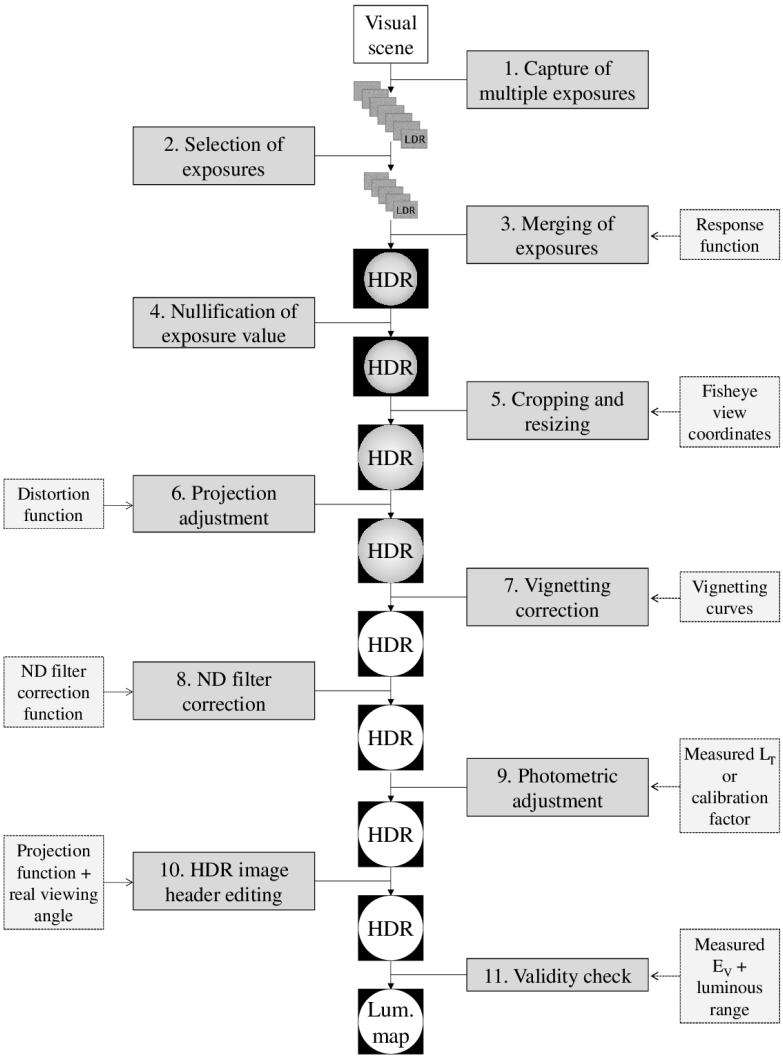


Figure 1. Step-by-step procedure to create a 180° luminance map from a visual scene with daylight using HDR photography.

Some calibration material, such as the camera response function or the vignetting curves, has to be defined prior to executing the procedure. The methods used to derive such calibration material are explained in the one-time setup (2.3). These steps should be performed only once per equipment, and can be used afterwards for each luminance map of a daylit scene generated with the same equipment. Therefore, the specific equipment required for the one-time setup (a color chart, a panoramic rotation unit and a sliding plate

to move the camera on the tripod, and a stable and bright light source in a dark room or a stable overcast sky simulator with a semi-circular platform) should only be available once. The rest of the equipment will always be needed for the HDR image generation and the HDR image calibration, except for the ND filter, of which the use depends on the lighting conditions.

3. One-time setup

1. Determination of the no-parallax point, real viewing angle, and fisheye view coordinates

The no-parallax point or entrance pupil point, sometimes wrongly referred to as the nodal point (Kerr 2008), is the point of the lens at which the rays entering the lens should converge. For traditional lenses, this point can be determined using a tripod with a panoramic rotation unit and a sliding plate on which the camera is set, as well as two vertical markers aligned with the center of the rotation unit, in front of the camera (Jacobs 2012). If the center of rotation of the camera coincides with the no-parallax point, the rear marker stays hidden by the one in front as the camera rotates (Figure 2).

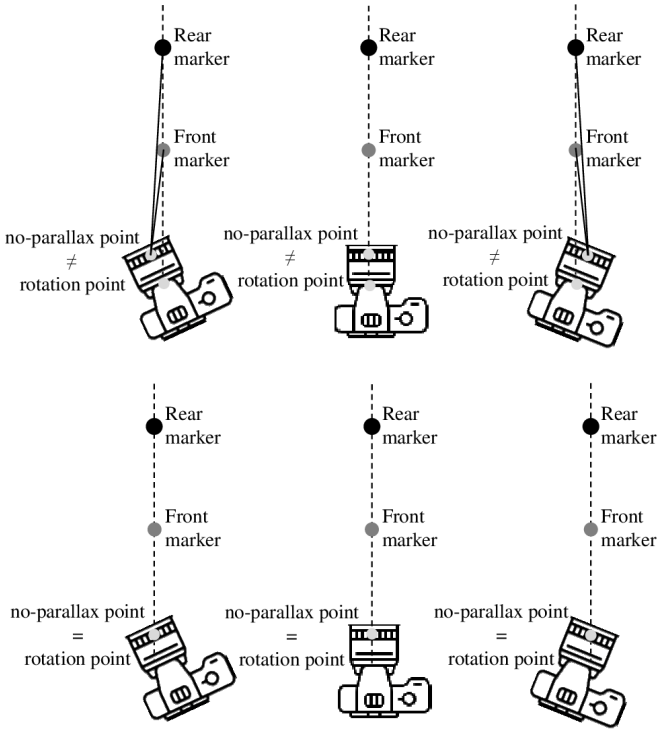


Figure 2. Setup of the equipment to evaluate the no-parallax point.

In photography, knowing the position of the no-parallax point is important when panoramic images are captured by rotating the camera for instance. For fisheye lenses, the no-parallax point is unfortunately not unique, and slides along the lens optical axis, closer to the front of the lens as the angle of view increases (Anderson 2006). There is therefore a range of least-parallax points. For the following steps, one of the least-parallax points (i.e. the one in the middle of the range located 2 mm in front of the lens gold ring) is selected, and the hypothesis is made that this point is the lens no-parallax point. The camera has to be rotated around this hypothesized no-parallax point in the future to avoid parallax error, namely a difference in the apparent relative position of objects due to a displacement of the line of sight.

Besides the fact that the edge of a fisheye view is in general blurry, the real viewing angle of a fisheye lens might not be exactly 180° and the center of a fisheye view might not be exactly at the center of the image (Jacobs 2012). To determine the total viewing angle of a fisheye lens, the no-parallax point has to be positioned between two reference grids. The no-parallax point should be aligned with the middle vertical lines of both grids, and centered at equal distance from these grids, so that the spacing between two lines of the grids corresponds to one degree in the camera FOV (Figure 3).

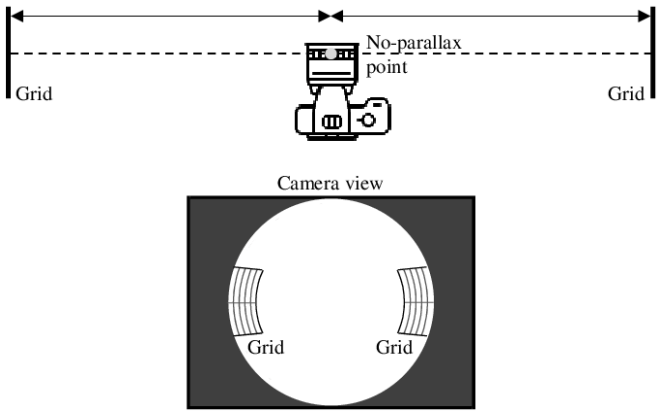


Figure 3. Setup of the equipment to evaluate the real viewing angle and the center of the fisheye view.

When the camera is looking at 0°, the two middle vertical lines of the grids should appear at the border of the fisheye LDR image, as well as when the camera is looking at 180°. In an image editing software, the distance in pixels between these lines in the 0° and 180° LDR images can be evaluated. This distance should be the same in both images. If additional vertical lines –over the 90° middle lines– appear in both images, the total viewing angle is thus larger than 180° and can be defined according to the number of additional lines visible.

Furthermore, by using any LDR image captured with the camera and lens, the fisheye view coordinates can be defined through an image editing software. The fisheye view coordinates are the coordinates (in pixels) of the bottom-left corner of the square encompassing the total viewing angle, as well as the fisheye view diameter. It should be noted that the origin of the coordinates system might be different between the image editing software (e.g. the origin is the upper left corner in *Gimp*, and in *Radiance*, the origin is typically the bottom left corner).

The real viewing angle of the example equipment is 186°, and the center of the fisheye view is slightly shifted towards the upper-right corner of the image.

2. Determination of the luminous range

The equipment luminous range is characterized by the minimal and maximal luminance values that the camera/lens combination can measure through HDR photography (Jakubiec et al. 2016a). In an LDR image, these extreme values are function of the sensitivity and the resolution of the camera sensor, of the lens, and of the ISO, aperture and exposure time settings. Since in HDR photography, the exposure time is varied, and a low ISO is recommended to minimize the noise in the image, the minimal and maximal luminance values measured in an HDR image depends on the camera sensor and lens, and on the aperture setting. Therefore, for a specific camera/lens combination, the luminous range can be defined for each aperture.

The minimal luminance value, namely the lower limit of the luminous range, should theoretically be zero. Due to noise and potential stuck pixels however, a slightly higher value should be expected. For typical indoor daylit scenes though, the noise floor at the lower end of the luminous range should not matter much.

To determine the maximal luminance value that can be captured for one aperture, a sequence of multiple exposures (see 2.4.1) of a very bright light source such as the sun has to be captured in the center of the fisheye view to avoid the vignetting effect. Exposures are then selected (see 2.4.2), and an HDR image is generated from the sequence (see 2.4.3). The maximal luminance value is defined as the peak (maximal) luminance in this HDR image, which can be retrieved using *falsecolor*. As the aperture size increases, the maximal luminance value decreases. A larger aperture size will indeed allow more light to fall on the sensor in a given period of time. This will cause more images in a sequence of multiple exposures to be overexposed, and thus to display a reduced contrast between the bright light source and the background. The dynamic range of the final HDR image will then be lower for a large aperture size than for a small aperture size.

Attention should be paid to the fact that Radiance uses the equal-energy white point [(x, y, z) = (0.33, 0.33, 0.33)] for its calculations, and slightly different RGB

primaries than sRGB primaries. Consequently, a luminance outputted by Radiance-based programs, such as *ximage*, *falsecolor* and *evalglare*, is calculated according to equation 1.

$$L = 179 * (R * 0.2651 + G * 0.6701 + B * 0.0648) \quad (1)$$

where L is the luminance of the pixel [cd/m²];
179 is the standard luminous efficacy [lm/W] in Radiance;
R, G, and B are the spectrally weighted radiance of the pixel [W/m²sr];
0.2651, 0.6701, 0.0648 are calculated from CIE chromaticities for the reference primaries (Radiance primaries) and the equal-energy white point as used by Radiance.

Most HDR image merging programs, such as *hdrgen* and *Photosphere*, use sRGB as their default output color space. sRGB white point is the one from CIE Standard Illuminant D65 [(x, y, z) = (0.3127, 0.3290, 0.3583)], thus slightly different from the equal-energy white point. Consequently, luminance calculation from HDR images should be performed using equation 2, as it is executed in *Photosphere* (Inanici 2006).

$$L = 179 * (R * 0.2126 + G * 0.7152 + B * 0.0722) \quad (2)$$

where L is the luminance of the pixel [cd/m²];
179 is the standard luminous efficacy [lm/W] in Radiance;
R, G, and B are the spectrally weighted radiance of the pixel [W/m²sr];
0.2126, 0.7152, 0.0722 are calculated from CIE chromaticities for the reference primaries (sRGB) and the CIE Standard Illuminant D65 white point.

Although the difference between the two equations looks minor, the error in terms of luminance for these two equations was evaluated with the example equipment under LED lighting (color temperature of 5400K) using equation 3.

$$\varepsilon_L = \frac{|L_{HDR} - L_{meas}|}{L_{meas}} * 100 \quad (3)$$

where ε_L is the error in luminance [%];
L_{HDR} is the luminance derived from the HDR image using equation 1 or 2 [cd/m²];
L_{meas} is the luminance measured in the scene with a spectroradiometer [cd/m²].

In average, the error between the measured and HDR-derived luminance for 18 colored samples from a Macbeth chart was observed to be around two times larger for the luminance derived from the HDR image using equation 1 (8.8%) than for the luminance derived from the HDR image using equation 2 (4.6%). No luminance error difference was observed between the two equations for neutral (gray) samples (both 2.1%). Nevertheless, using *ximage* and *falsecolor* to retrieve luminance value is acceptable in a context of indoor scenes. Indeed, the visual environment inside buildings is relatively neutral, making the use of equation 1 acceptable. The line of code in *Radiance* to print the peak

(min. and max.) luminance values of an HDR image (*HDRfile.hdr*) with *falsecolor* in a false-colored HDR image (*HDRfile_peak.hdr*) is as follows:
> falsecolor -i *HDRfile.hdr* -e > *HDRfile_peak.hdr*

If the peak luminance in an HDR image generated with a specific equipment is near the upper limit of the equipment luminous range, the picture might exhibit pixel overflow. A solution to avoid pixel overflow is to use a ND filter (see 2.3.6).

The upper limit of the luminous range for the example equipment was evaluated for each useful aperture by capturing a sequence of 15 images (exposure time going from 1/8000 to 2 seconds) of the sun under clear sky conditions. These upper limits, shown in figure 4, are similar to the ones presented by Jakubiec et al (Jakubiec et al. 2016b).

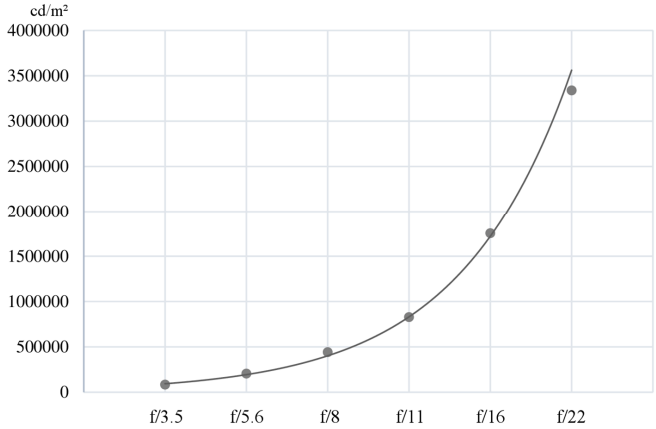


Figure 4. Maximal luminance values that can be captured through HDR photography with the example equipment for different apertures.

3. Determination of the response function

The camera response function is required to generate an HDR image when the LDR images are in the jpeg format, but not when they are in the raw format (see 2.4.1). The response function relates pixel values to incoming light quantities (Hirning 2014). More specifically, it matches radiance values from the scene (W/m²sr) to pixel values (0-255) for the RGB channels. Each camera has its specific response function, even cameras from the same model (Jacobs 2007).

To approximate the camera response function, several algorithms have been developed, amongst which the one from Debevec and Malik (Debevec and Malik 1997) which was later modified by Mitsunaga and Nayar (Mitsunaga and Nayar 1999), and the one from Robertson et al (Robertson et al. 2003). These algorithms rely on a series of

aligned exposures. By looking at the evolution of one pixel value across the exposures, one can sample the shape of the camera response function for the corresponding part of the curve. Using linear optimization (Debevec and Malik 1997) or a polynomial approximation (Mitsunaga and Nayar 1999) with several pixels, a smooth response function can be obtained for each channel (Reinhard et al. 2006). *hdrgen* and its implementation in *Photosphere* approximate the RGB camera response curves using Mitsunaga and Nayar's method, whereas *pfscalibration* offers the option to choose between Robertson's or Mitsunaga and Nayar's algorithms. These algorithms all require a sequence of LDR images taken with a specific camera as input to derive the response function of that camera.

Since the response function depends on the white balance setting of the camera and the principal lighting source (Jacobs 2012), it should be derived once in correct conditions, and reused for all HDR images generated from the same camera with the same white balance setting ("daylight - 5200K" for daylight scenes) and under a similar main lighting source (daylight, in this case). The scene photographed for the sequence of multiple exposures has to be chosen carefully to optimize the response recovery. In the case of daylight, it is recommended to select an interior daylit scene with large and smooth gradients throughout interior and exterior views, with very bright and dark areas, and as non-chromatic as possible (Figure 5) (Inanici 2006; Inanici and Galvin 2004; Jacobs 2012; Reinhard et al. 2006). Furthermore, large apertures of the lens (e.g. f/3.5 or f/5.6) increase the probability of biasing the response curve derivation due to the vignetting effect on the LDR images of the sequence (see 2.3.5). To limit this effect, a small aperture such as f/16 should be preferred. At last, the indications for the capture, selection, and merging of exposures (see 2.4.1, 2.4.2, and 2.4.3) should be taken into consideration for the response function derivation.



Figure 5. Example of a visual scene appropriate for the derivation of the camera response function.

Once a sequence of LDR images is captured, the RGB response curves of the camera are evaluated by *hdrgen* on the basis of this sequence. The line of code to generate the camera response function (*response_function.rsp*) from a sequence of multiple exposures (*LDRfiles_*.jpg*) with *hdrgen* is as follows:
> hdrgen *LDRfiles_*.jpg* -o *HDRfile.hdr* -r *response_function.rsp* -a -e -f -g

The algorithm outputs approximated response curves in an .rsp text file containing the polynomial order of the three RGB curves and their coefficients. Attention should be paid to the direction in which the coefficients are printed since it is reversed between *hdrgen* (from kN to k0) and *Photosphere* (from k0 to kN) for instance.

Regarding the example equipment, three response functions were derived from three scenes that matched the required characteristics, similar as the scene in figure 5. RGB response curves were derived for the three scenes and compared. They showed very similar behavior (Figure 6). Final compound camera response curves for the example equipment were derived from the means of the three curves. An .rsp text file was created that contained the polynomial order of the mean RGB curves and their coefficients in the order of *Radiance*.

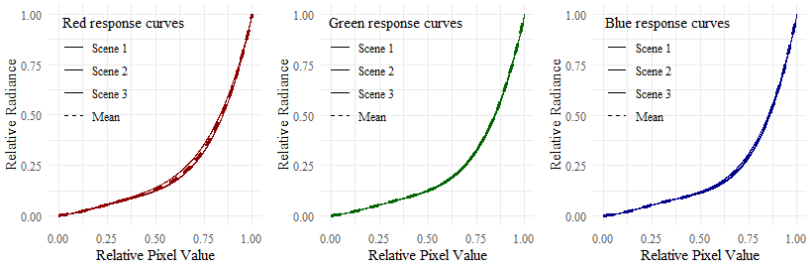


Figure 6. RGB response curves derived with hdrgen for three different visual scenes captured with the example equipment and mean RGB response curves.

4. Determination of the projection and distortion functions

Fisheye lenses project 3D scenes on 2D images with a specific projection type (Figure 7) amongst equidistant (i.e. equiangular), equisolid-angle (i.e. equal-area), orthographic (i.e. hemispherical), and stereographic (i.e. planispheric) (Cauwerts et al. 2013).

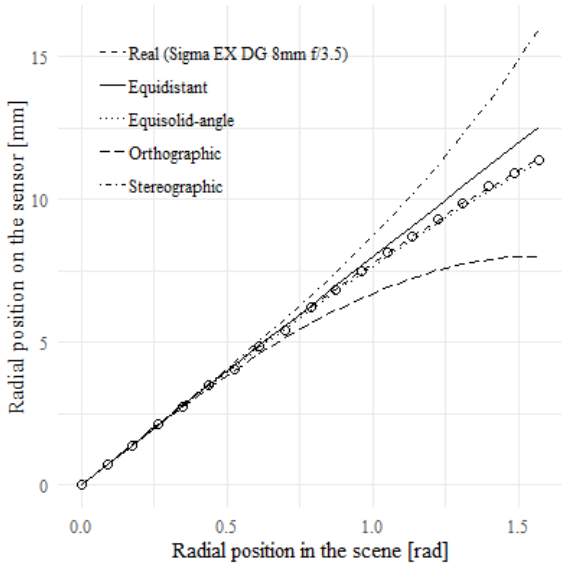


Figure 7. Theoretical projection types to project a 3D scene on a 2D image and measured projection of example equipment.

The two most widely implemented projection types in commercially available fisheye lenses nowadays are the equidistant and equisolid-angle ones. Although each lens model is related to one theoretical projection, the implementation of the projection is not perfect in practice and suffers from small inaccuracies. For several applications, the geometrical accuracy of an HDR image is primordial, hence the importance to know the real projection function of the lens and to be able to adjust it if need be. For instance, the calculation from an HDR image of any discomfort glare metric using *evalglare* (Wienold and Christoffersen 2006) relies on two geometrical quantities, i.e. the solid angle and the position index of the glare source(s). But the solid angle and the position index vary according to the projection function of the lens. *Evalglare* is currently able to devise these geometrical quantities for fisheye lenses using equidistant and orthographic projection types (Wienold 2012). Consequently, there is a need to adjust the projection of an HDR image if the lens that was used offers another projection type than those supported by *evalglare*. For applications where geometry of the visual scene is relevant, such as glare studies, it is generally recommended to have an HDR image with an equidistant projection.

Before adjusting the projection of an HDR image, the first step is to define the real projection function of the lens. The information about the theoretical projection type of the lens might be given by the manufacturer. Otherwise, one relatively easy way to verify this information is to measure it manually.

A first option to measure it is to place the camera facing a 90° corner of a room, with its hypothesized no-parallax point at equal distance between the two walls (Figure 8). A scale is measured and printed on the walls, so that there is a reference in the scene marking each 5° angle of the 180° FOV, and a picture is captured in this setup. The radial position (in pixels) of the 5° angle references are extracted from the LDR image using an image editing software, and translated to the absolute radial position (in mm) on the camera sensor.

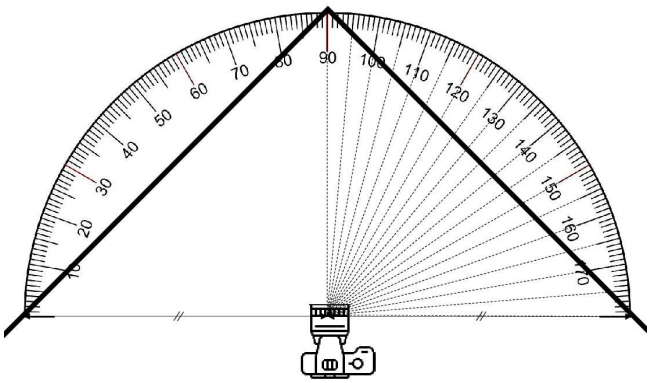


Figure 8. Setup of the equipment to evaluate the real projection function.

A second option to measure manually the projection type of the lens requires a panoramic rotation unit. First, an LDR image of a vertical marker on the horizon line of the fisheye view has to be taken every 5° by rotating the camera on its hypothesized no-parallax point until the lens FOV is covered. The radial position (in pixels) of this vertical marker can be easily extracted from each picture using an image editing software, and translated to the absolute radial position (in mm) on the camera sensor.

For both methods, each measured radial position is related to a certain angle of the lens, and can be displayed on a graph to be compared with the theoretical projection types (Figure 7). By computing the Mean Squared Error (MSE) of each theoretical projection function against the measured values, the theoretical projection type of the lens can be defined as the one producing the smallest MSE. Once the theoretical projection type is known, the real projection function of the lens can be derived from the measured values with a regression based on the theoretical projection model, as shown in equation 4 for a theoretical equisolid projection.

$$r = a * f * \sin\frac{\theta}{b} \tag{4}$$

where r is the distance on the sensor from the optical axis [mm];
f is the focal length of the lens [mm];
θ is the entrance angle measured from the optical axis [rad];
a and b are the parameters of the real projection function to be defined.

There exist other methods to derive the real projection function of a lens:

- the method for which the no-parallax point of the camera/lens is set at the center of a semi-circular platform, on which references are positioned every 5° in the 180° FOV of the camera (Cauwerts et al. 2013). By retrieving the pixel coordinates of each 5° reference of the platform from an LDR image taken by the camera, the real projection function of the lens can be derived.
- the method for which the camera/lens is set in front of a planar reference grid with its no-parallax point aligned with the center of the grid at a known distance from it (Geisler-Moroder et al. 2016). By evaluating the distances between each grid line and the middle one, and comparing these distances with the pixel distances retrieved from an LDR image of the grid, the real projection function of the lens can be derived.

If the real projection function differs from the two most common theoretical projection functions (i.e. equidistant or orthographic) and if the application of the HDR image requires geometrical accuracy, a distortion function should be derived and applied to the HDR image to adjust its projection. The distortion function establishes the displacement that should be applied to a pixel according to its original position to get an equidistant projection in an HDR image.

Since the equisolid-angle type is one of the two most widely available lens types, the distortion function to adjust an HDR image with an equisolid-angle projection to an HDR image with an equidistant projection has already been defined (Ward 2016), as shown in equation 5.

$$r_{equidistant} = \frac{2}{\pi} * \sin^{-1}(\sqrt{2} * r_{equisolid-angle}) \quad (5)$$

where $r_{equidistant}$ is the normalized distance from the optical axis for an equidistant projection [0 - 0.5];
$r_{equisolid-angle}$ is the normalized distance from the optical axis for an equisolid-angle projection [0 - 0.5].

For fisheye lenses having another projection type than the equisolid-angle one, the distortion function can be approximated by a second-order polynomial without intercept, as shown in equation 6. The approximation is done on the basis of the adjusted radial position of the pixels and their original radial position, both normalized in the [0 - 0.5] range for the distortion function to be easily applied afterwards. The adjusted radial positions can be derived using the theoretical equidistant projection function, whereas the original radial positions are either derived from the real projection function previously defined, or from the measured radial position of the vertical marker in the series of LDR images using the panoramic rotation unit for instance.

$$r_{equidistant} = a * r_{original}^2 + b * r_{original} \quad (6)$$

where $r_{equidistant}$ is the normalized distance from the optical axis for an equidistant projection [0 - 0.5];
$r_{original}$ is the normalized distance from the optical axis for the real projection of the lens [0 - 0.5];
a and b are the parameters of the distortion function to be defined.

At last, the distortion function has to be applied on the pixels of the HDR image to adjust. For this purpose, the distortion function is stored in the fisheye_corr.cal file (Ward 2016) in place of the *mapsolid(r)* equation. The default distortion function is the equisolid-to-equidistant function, but it can be changed if need be. Besides adjusting the projection of an HDR image, the application of the fisheye_corr.cal file also sets the pixels of the HDR image outside the 180° FOV to black.

Regarding the example equipment, the Sigma EX DG 8mm f/3.5 lens was said to have an equisolid-angle projection type by the manufacturer. The real projection function of the lens was measured manually and defined in equation 7.

$$r = 1.97 * f * \sin\frac{\theta}{1.94} \quad (7)$$

where r is the distance on the sensor from the optical axis [mm];
f is the focal length of the lens [mm];
θ is the entrance angle measured from the optical axis [rad].
Since this real projection function is close to the theoretical equisolid projection function, the default distortion function, namely the equisolid-to-equidistant one, is stored in the fisheye_corr.cal file.

5. Determination of the vignetting curves

The vignetting effect in photography is the brightness decrease that can be observed from the center of a picture towards its periphery, especially when a fisheye lens is used (Reinhard et al. 2006). This vignetting effect depends on the aperture of the lens, with small apertures yielding little vignetting (Inanici 2009). For large apertures, though, the effect can be as large as a 70% luminance loss at the periphery of the fisheye image (Cauwerts et al. 2013). Cauwerts et al.'s and Jakubiec et al.'s studies (Cauwerts et al. 2013; Jakubiec et al. 2016b) suggest that the vignetting curves determined for two devices of a similar brand and model are interchangeable. It is however recommended to derive proper vignetting curves for the device in use since optic materials are not exactly identical, and can contain defects and aberrations (Stanley 2016), and production processes can also change.

The vignetting curve derivation requires evaluating the progressive luminance loss towards the periphery of the fisheye view of an HDR image. For each aperture that will be used later on, a vignetting curve should be determined. There exist at least two

common methods of deriving these vignetting curves, which require different equipments.

Vignetting curves derivation from a semi-circular platform. The semicircular platform is made of evenly distributed uniform gray targets in a room with non-flickering, constant, and indirect lighting (Cauwerts et al. 2013). For each aperture needed, a sequence of multiple exposures (see 2.4.1) of the scene with the targets located at known angles in the FOV of the lens (e.g. every 5°) is captured. The luminance value of the center of each target is also measured with a spot luminance meter positioned in such a way that its rotating center is at the same place as the hypothesized no-parallax point of the camera (Figure 9).

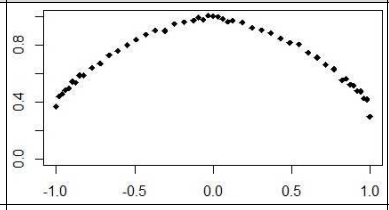
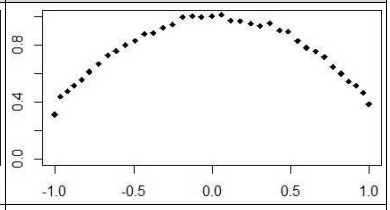
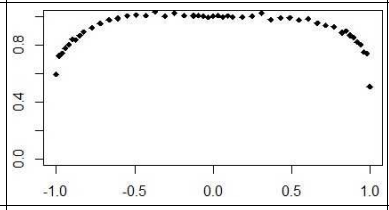
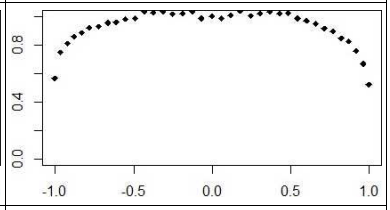
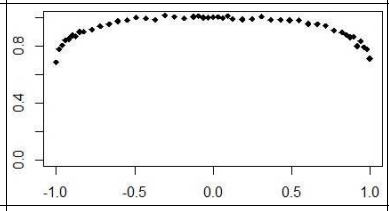
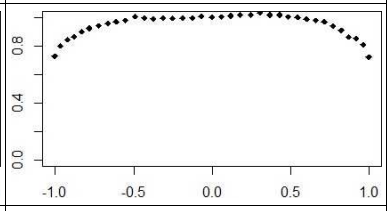
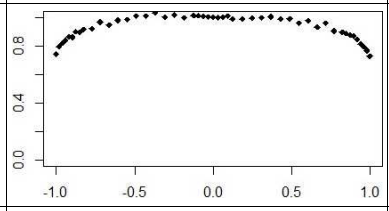
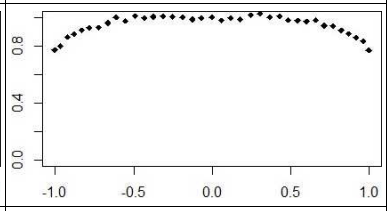
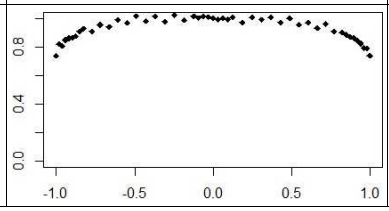
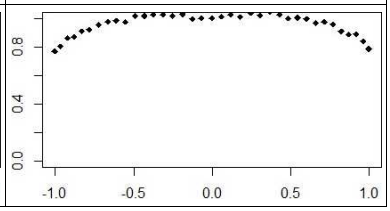


Figure 9. Setup of the equipment for the first method to evaluate the vignetting curves.

If the lighting stability over time is imperfect, a horizontal illuminance meter is added on the platform to record an illuminance value each time a sequence of multiple exposures is captured. This value is compared to the illuminance value recorded when the spot luminance measures are taken. The spot luminance measures can then be weighted with the percentage difference in horizontal illuminance to account for unstable lighting conditions if need be.

Exposures are selected (see 2.4.2), and HDR images are generated (see 2.4.3) and calibrated in *Photosphere* with the spot luminance measurement made on the central target (see 2.5.9). On the basis of the ratio of the luminance value extracted from the HDR image to the luminance value measured in the scene for each target in the lens FOV, the vignetting curves can be drawn (Table 2). Using the radial position of the targets in the image, normalized in a [-1 - 1] range, and the corresponding luminance ratios, an even-order polynomial is derived to approximate the vignetting effect while ensuring symmetry (Jacobs 2012). The larger the aperture, the larger the vignetting effect, and the lower the degree of its polynomial.

Table 2. Comparison of the vignetting curves of the example equipment for different apertures derived with the two suggested methods; in the graphs, the x axis represents the normalized position of the pixel from the center of the fisheye view [-1 – 1], and the y axis represents the relative luminance [0 – 1].

f/	Vignetting curves derivation from a semi-circular platform	Vignetting curves derivation by rotation
3.5		
5.6		
11		
16		
22		

Vignetting curves derivation by rotation. The second method to derive the lens vignetting curves is more commonly used (Cai and Chung 2011; Hirning 2014; Inanici 2006; Inanici and Galvin 2004; Jakubiec et al. 2016b; Van Den Wymelenberg 2012). It requires a panoramic rotation unit and a constant, non-flickering, and uniform target, which could

be either a stable and bright light source in a dark room, or a gray card in a stable lighting environment. The camera is positioned facing the target on a tripod, with the hypothesized no-parallax point aligned with the center of rotation of the panoramic rotation unit (Figure 10).



Figure 10. Setup of the equipment for the second method to evaluate the vignetting curves.

A sequence of multiple exposures is captured (see 2.4.1). The camera is then rotated by steps (e.g. every 5°) until the camera FOV is covered, and a sequence of multiple exposures is captured at each step. After selecting the exposures (see 2.4.2) and generating the HDR images (see 2.4.3) for each rotation step, the luminance value of the target for each step can be extracted, with the target having a different radial position in each image. The vignetting curve corresponding to one aperture is defined by an even-order polynomial that approximates the ratio of the luminance value of the target at a specific radial position in the image (thus derived from the HDR image of the corresponding rotation step) to the luminance value of the target at the center of fisheye view image (thus derived from the HDR image facing the target) for each radial position in the image normalized in a [-1 - 1] range. This procedure is conducted for each aperture needed.

To counteract the vignetting effect shown by the vignetting curves, the pixels at the periphery of the fisheye view in the HDR image have to be compensated. This is done by multiplying the RGB values of each pixel according to the distance of the pixel from the fisheye view center defined in equation 7, by a factor derived from the inverse of the vignetting curve defined in equation 8, as shown in equation 9.

$$z_i = \frac{\sqrt{(x-x_c)^2+(y-y_c)^2}}{R} \tag{7}$$

$$f_v = \frac{1}{a*z_i^k+b*z_i^{k-1}+\cdots+n*z_i+1} \tag{8}$$

$$r_o = f_v * r_i(1)\ ;\ g_o = f_v * g_i(1)\ ;\ b_o = f_v * b_i(1) \tag{9}$$

where x and y are the coordinates of the pixel [pixels];

x_c and y_c are the coordinates of the center of the fisheye view [pixels];

R is the radius of the fisheye view [pixels];
z_i is the distance of the pixel from the optical axis [pixels];
a to n are the parameters of the vignetting polynomial to be defined;
f_v is the vignetting correction factor;
$r_i(1)$, $g_i(1)$ and $b_i(1)$ are the spectrally weighted radiance of the pixel before the vignetting correction [W/m²sr];
r_o, g_o, b_o are the spectrally weighted radiance of the pixel after the vignetting correction [W/m²sr].

A .cal text file to apply the vignetting correction is created for each aperture. Each .cal file contains equations 7, 8, and 9, with the parameters of the vignetting polynomial defined according to the aperture.

The vignetting curves for the example equipment were derived using both methods. As seen in Table 2, the two methods provided very similar results, with a maximum of around 65% luminance loss at the periphery of the fisheye image for an aperture of f/3.5.

6. Determination of the ND filter correction function

Pixel overflow, also referred to as sensor blooming, consists of a pixel reaching its limited charge capacity, thus propagating the extra charge to surrounding pixels. To prevent this issue, ND filters should be used when a bright light source having a luminance larger than the upper limit of the equipment luminous range (see 2.3.2) is in the captured FOV. These filters reduce the amount of light hitting the sensor, permitting it to capture larger luminance values. ND filters exist with different density. The transmittance information is given by the ND number according to equation 10. For instance, a filter with ND 3.0 has a transmittance of 0.1%, and a filter with ND 0.3, a transmittance of 50%. In lighting research, we recommend using filters with ND 3.0 (daylighting with the sun in the FOV) or lower ND numbers (daylighting and electric lighting).

$$Transmittance_{ND\ filter} = 10^{-ND\ number} \quad (10)$$

Although these filters are said to be neutral, they tend to introduce a chromatic shift in the recorded pixel values, especially in the blue channel (Cauwerts 2013). This chromatic shift slightly affects the luminance values of the HDR image (Jakubiec et al. 2016a), since the luminance values are evaluated from the RGB values through a luminance conversion function, as shown in equations 1 and 2.

Although the correction of the chromatic shift for the entire ND filter spectrum would require the use of a spectroradiometer, the chromatic shift can be corrected for the visible portion of the ND filter spectrum relatively easily. A color transform function which maps the RGB components of an image with the filter to the RGB components of an image without it can be derived and applied to the HDR image to counterbalance the

shift (Cauwerts 2013; Inanici 2010; Jones and Reinhart 2017; Stumpfel et al. 2004). For this purpose, a sequence of multiple exposures (see 2.4.1), in which a Macbeth color chart is photographed under stable daylight conditions, has to be captured once with and once without the ND filter. To maximize the radiance range that is used to derive the ND filter correction function, several daylit scenes (e.g. inside and outside) containing the Macbeth color chart should be captured twice (i.e. with and without the ND filter), with the chart in the center of the fisheye view to avoid the vignetting effect. The exposures are then selected (see 2.4.2) and merged into HDR images (see 2.4.3). By comparing the RGB components of each color patch of the Macbeth chart in the HDR images generated with and without the ND filter, the chromatic shift can be estimated. The ND filter correction function is approximated by a linear regression without intercept for each channel (Figure 11). Besides the chromatic shift correction, this ND filter correction function also takes into account the brightness scaling arising from the use of an ND filter and correct for it. The three linear ND filter correction functions for the three channels are stored in a .cal text file.

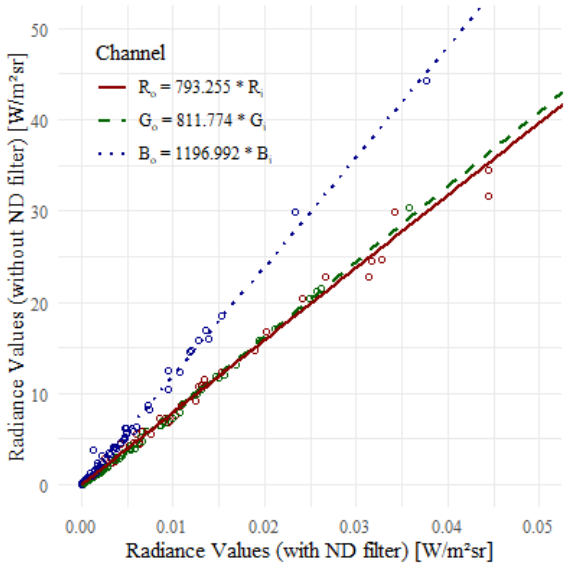


Figure 11. Linear regressions estimating the RGB chromatic shifts for the visible portion of the spectrum when the ND filter of the example equipment is used.

A Kodak Wratten 3.0 ND filter was used with the example equipment when the sun was in the FOV. To derive the ND filter correction function corresponding to each channel, three scenes, including a Macbeth chart, were captured with and without the filter: one inside under an overcast sky, one inside under a clear sky, and one outside under an overcast sky. The three resulting linear functions are shown in figure 11.

4. HDR image generation

1. Capture of multiple exposures

To generate an HDR image, a sequence of multiple exposure LDR images has to be captured, with the camera having its settings set as defined in table 1. This sequence extends from an overexposed image, almost white, to an underexposed image, almost black, and should contain 15 or more LDR images separated by 1 or more EV stop (Figure 12). The order in which the LDR images are captured could be reversed, and the number of LDR images could be reduced depending on the lighting conditions of the scene. The exposure variation (1 or more EV stop) between the LDR images is done by changing the exposure time between photographs. Changing the aperture would increase problems associated with vignetting (Reinhard et al. 2006) and shutter speed is a more reliable measure than aperture size (Inanici 2006). For daylighting conditions, it is recommended to avoid exposure times longer than 2 seconds to keep the sequence as short as possible and ensure stable conditions throughout the sequence. The aperture should be set according to the scene, although it is recommended not to use extreme aperture sizes. On the one hand, small aperture sizes (high numerical apertures) are correlated with greater potential for lens flare (Jakubiec et al. 2016b). On the other hand, large aperture sizes (small numerical apertures) suffer from a low maximum captured luminance value (Jakubiec et al. 2016b) and a large vignetting effect (Cauwerts et al. 2013). A mid-range aperture size, such as f/8 or f/11 for fisheye lenses, can be used as a trade-off.



Figure 12. Sequence of 16 multiple exposure LDR images separated by 1 EV stop captured with the example equipment.

The camera should be set on a tripod to avoid misalignment problems during the HDR generation (Reinhard et al. 2006). Depending on the number of LDR images to capture, the images can be either saved in jpeg format, which is a compressed file, or in raw format, which is uncompressed and requires around four times more storing memory. The benefit of raw images is that they contain unprocessed electrical charge information directly from the image sensor (Stanley 2016). Therefore, the generation of HDR images from raw files does not require the preliminary derivation of the response function. *raw2hdr* program, available in the *Radiance* suite, is the equivalent of *hdrgen* for raw images input; all following calibration steps are similar. Although jpeg compression causes the loss of much color data (4096 tonal levels in raw files compared to 256 levels of information for each channel in jpeg files (Stanley 2016)), it is decent at preserving luminance data, and is much more convenient to store. Moreover, when shooting in raw format, the maximum burst during continuous shooting, namely the number of continuous shots that can be taken by the camera without stopping, might be limited to a number lower than the 15 recommended LDR images.

To capture a sequence of multiple exposures, there are three main options. The first one is the manual bracketing, which means that the change of exposure between each image of a sequence is done manually on the camera by modifying the exposure time. This option is not recommended, since the manual adjustment significantly slowdowns the sequence capture and will most probably cause alignment problems between the images of a sequence. The second option is the automatic bracketing by the camera. This option uses the Automatic Exposure Bracketing (AEB) feature of the camera to directly capture a sequence of multiple exposures. However, not all cameras offer this feature, and most of the time, the maximum number of images that can be captured are limited to 3 or 5. Although it is recommended to capture at least 7 images, 5 images might be sufficient for specific scenes with few contrast. The last option, which is the one recommended, is the automatic bracketing with a remote control. The bracketing settings are defined through a bracketing software, such as *qDslrDashboard* (Hubai 2014), installed on a computer that remotely controls the camera. The capture of multiple exposures is done without interruption and with no risk of movement between the images, and the number of images in a sequence is not limited. Furthermore, in cases where the sun is in the FOV, the use of a ND filter is recommended (see 2.3.6). This filter has to be positioned between the lens and the camera sensor, but it should be handled very carefully. The ND filter has indeed to be kept perfectly clean in order that it adds no light scattering to what is already produced by the lens.

At last, the sequence capture should always be accompanied by at least one spot luminance measurement (Van Den Wymelenberg 2012) and one vertical illuminance measurement (Pierson et al. 2017b). The spot luminance should be measured on a mid-range gray card located in the scene during the sequence capture with a spot luminance meter. This measure will be used at the end of the calibration process to scale the relative luminance values embodied in the HDR image to the absolute luminance values of the scene (see 2.5.9). Furthermore, the vertical illuminance value should also be measured during the sequence capture, and as close as possible to the camera lens but without obstructing it. This illuminance value is necessary to check the validity of the corresponding calibrated HDR image (see 2.5.11).

With the example equipment, times of exposure expanding from 1/8000 to 2 seconds and an aperture of f/11 are usually chosen to capture a sequence of 15 multiple exposures separated by 1 EV. The camera, set on a tripod, is remotely controlled through *qDslrDashboard*. Two vertical illuminance measurements are taken, one just before and one just after the sequence, and two or three spot luminance measurements are taken during the sequence on mid-range grey targets in the scene.

2. Selection of exposures

To ensure that a sequence of multiple exposures contains enough over- and underexposed LDR images and that the entire luminance range of the scene is recorded, it is

recommended to capture the largest possible bracketed sequence (Van Den Wymelenberg 2012). However, only LDR images bringing useful information should be inputted in the merging algorithm in order to accelerate the HDR generation process and make it more stable. Therefore, a selection of LDR images has to be made on the captured sequence. *hdrgen* and *Photosphere* offer a -x option to automatically ignore unnecessary exposures. However, it is recommended not to use this option and to make the selection manually since this -x option was developed as a timesaver feature and lacks accuracy.

The LDR images have to be selected in such a way that the darkest exposure of the useful sequence has no R, G, and B pixel values greater than 228, and the lightest exposure has no R, G, and B pixel values below 27 (HDRI mailing list as of February 2012). These RGB threshold values are preferred over the 20, 200 RGB thresholds as they have been empirically recognized to achieve better results. The selection rules consist therefore of restraining the sequence from the darkest overexposed image having no pixel value below 27 to the lightest underexposed image having no pixel value over 228. When working on discomfort glare, the second rule is especially important. The darkest exposure having no white pixel means that the total luminance of the brightest light source in the FOV has been captured by the sequence.

More practically, this manual selection could be automated. One approach consists of applying a mask on each LDR image so that all pixels outside of the fisheye view are set to a neutral color such as black (Van Den Wymelenberg 2012). The exact number of black pixels located outside of the fisheye view is known. Then, the pixels of the image having a value below 27 and over 228 are counted. The images having no white pixel (>228) can be directly identified, and those having no black pixel (<27) can be identified by subtracting the number of black pixels located outside of the fisheye view from the number of black pixels counted in the image. In some cases, every overexposed image of a sequence might contain black pixels, or inversely for white pixels. The useful sequence will thus include all over- or underexposed LDR images.

Regarding the sequences of 15 LDR images collected with the example equipment, the selection was automated through an R script (Ihaka and Gentleman 1996) on Linux, which consisted of applying a black mask on the image and counting the pixels before returning the list of selected exposures bringing useful information for the HDR image generation.

3. Merging of exposures

The merging process is based on the principle that each image in a sequence of multiple exposures will have different pixels properly exposed, but each pixel will be properly exposed in one or more images. Therefore a weighting system is used on the pixels of each image to cut out the influence of over- or underexposed pixels and increase the influence of correctly exposed ones in the merging of the exposures.

In summary, the HDR generation process from jpeg files consists first of linearizing the pixel values in each LDR image by canceling out the camera response function. Then, the pixel values of each LDR image are divided by the image exposure time to bring the pixel values into the same domain. At last, each pixel value of each LDR image is weighted according to its value, and the resulting pixel values of the HDR image are the averages across exposures of the weighted corresponding pixel values (Reinhard et al. 2006).

hdrgen or *pfscalibration* are examples of merging algorithms which require the camera response curve and a sequence of multiple exposures to generate an HDR image. The choice between these two tools should have no impact on the quality of generated HDR images since both Debevec and Malik's and Robertson's algorithms have been proved to perform equally well (Jacobs and Wilson 2007). However, other HDR merging software such as *Bracket*, *Luminance HDR*, and *Picturenaut*, have been shown to produce poorer results (Stanley 2016) and should therefore be avoided. Moreover, if a proper camera response function has not been previously derived as recommended (see 2.3.3), one will be created by the algorithm based on the inputted sequence of multiple exposures. Not deriving a proper camera response function will most probably cause a larger error in the HDR image since the captured scene that is then used to derive a substitute response function was not optimized.

hdrgen offers some features amongst which the main ones are the automatic exposure alignment (-a), the exposure adjustment (-e), the lens flare removal (-f), the ghost removal (-g), and the under- or overexposed image removal (-x). When taking a tripod-stabilized sequence, the automatic exposure alignment (-a) feature should be turned off to avoid unnecessary manipulations of the HDR image. Similarly, for auto-bracketed sequence, the exposure adjustment (-e) feature should be avoided, especially if the camera reproducibility test was successful (see 2.1.2). This feature adjusts for errors in the camera exposure settings by fine-tuning the scalar multiplier between exposures. Moreover, if the captured scene is prone to lens flare, namely scattered light from bright light source which results in a slightly fogged or starred appearance in the image (Figure 13), or ghosts, i.e. objects or subjects moving during the sequence, the corresponding feature (-f and -g) should be activated in *hdrgen* to remove these artifacts. In any case, the selection of LDR images should not be executed through the image removal (-x) feature to avoid removing images that could bring useful information. The line of code to merge the selected LDR images (*LDRfiles_*.jpg*) into an HDR image (*HDRfile.hdr*) with the predefined camera response function (*response_function.rsp*) using *hdrgen* is as follows:

> hdrgen *LDRfiles_*.jpg* -o *HDRfile.hdr* -r *response_function.rsp* -a -e -f -g

HDR images generated by *hdrgen* or *Photosphere* include a header, where the settings and parameters of the image are stored (Jacobs 2007). The line of code to visualize the header information of an HDR image (*HDRfile.hdr*) using *getinfo* is as follows:

> getinfo *HDRfile.hdr*

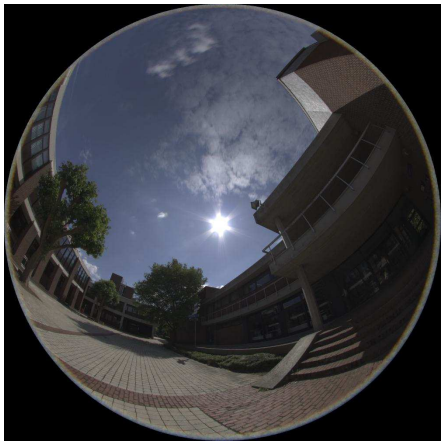


Figure 13. Example of visible lens flare due to the sun in the field of view.

The header information includes the view type, the viewing angle and the exposure value. It must be noted that the view type and viewing angle written in the header automatically are typically not correct, since this information cannot be retrieved from the EXIF information of the LDR images. Therefore these header entries have to be modified to the correct values later on (see 2.5.10). In addition, some programs of *Radiance* will interact with or deactivate the header entries when applied to the HDR image. This is the case for instance with *pcomb* and *pcompos*, which will mark the exposure or view type entries in the header as "invalid" by adding a tabulator. The data contained in an HDR image will therefore be wrongly interpreted since by default, an exposure value of 1 is used when the exposure value cannot be extracted from the header. It is therefore required to nullify the exposure entry in the header (see 2.5.4).

5. HDR image calibration

4. Nullification of exposure value

To prevent the issue of wrong interpretation of the exposure, it is recommended to include the exposure value directly in the pixel values, and either set the exposure value in the header to 1 or remove the exposure entry completely. The recommended method is to use *ra_xyze*, which includes the exposure in the pixels and removes it from the header, as the first command applied after an HDR image is generated. The line of code to nullify the exposure value of an HDR image (*HDRfile.hdr*) using *ra_xyze* is as follows:
> ra_xyze -r -o *HDRfile.hdr* > *HDRfile_EVinpixel.hdr*

5. Cropping and resizing

To facilitate the manipulations applied to an HDR image, it is recommended to crop this image to a square encompassing the circular fisheye view (Figure 14).

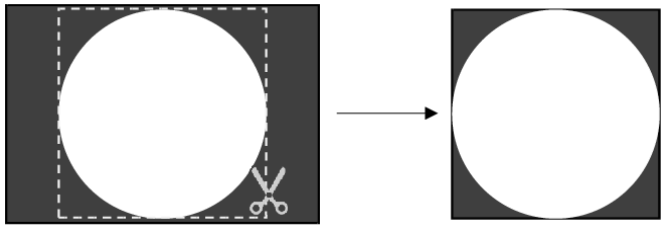


Figure 14. Cropping of an HDR image to a square encompassing the circular fisheye view.

Using the fisheye view coordinates defined during the one-time setup (see 2.3.1), the cropping of the HDR image is carried out using *pcompos*. The input values required are the coordinates (in pixels) of the bottom-left corner of the square encompassing the total viewing angle, as well as the fisheye view diameter (in pixels). The line of code to crop the HDR image (*HDRfile.hdr*) to a smaller pixel resolution (*diameter*) having the anchor point set as the bottom-left corner of the square encompassing the fisheye view (*xleft*; *ydown*) using *pcompos* is as follows:
> pcompos -x *diameter* -y *diameter HDRfile.hdr -xleft -ydown* > *HDRfile_cropped.hdr*

By applying this command, the header entries for the view type, the viewing angle and the exposure are marked as “invalid” and need to be adjusted later (see 2.5.10).

Moreover, there might be some applications for which the size of an HDR image is limited to a certain pixel resolution in order to avoid unreasonable computational processing time. This is the case for discomfort glare analyses with *evalglare*, since the computational performance drops when processing HDR images larger than 1500x1500 pixels. The resizing of an HDR image, which is optional and dependent on the final use of the HDR image, can be done through *pfilt* with the HDR image and the desired size in pixels as inputs. While using *pfilt*, the -1 feature should be activated to allow only one pass on the file and avoid the addition of an exposure entry in the header of the HDR image. The line of code to resize the HDR image (*HDRfile.hdr*) to a smaller resolution (*xdim*, *ydim*) using *pfilt* is as follows:
> pfilt -1 -x *xdim* -y *ydim HDRfile.hdr* > *HDRfile_resized.hdr*

Cropping and/or resizing an HDR image implies that the new size and new center coordinates have to be considered in the .cal files that have been determined during the one-time setup (e.g. the .cal files for the vignetting correction).

6. Projection adjustment

In applications for which the geometry of the visual scene is relevant, it is often preferred to have an HDR image with one the two most common theoretical projections (i.e. equidistant or orthographic). If the real projection function of the lens differs from these projection types, the projection of the HDR image can be adjusted thanks to the distortion

function stored in the fisheye_corr.cal file (see 2.3.4). The line of code to apply the projection adjustment to an HDR image (*HDRfile_equisolidproj.hdr*) using *pcomb* and the fisheye_corr.cal file (*fisheye_corr.cal*) containing the correct distortion function (by default, the distortion function encoded is the equisolid-to-equidistant distortion) is as follows:
> pcomb -f *fisheye_corr.cal HDRfile_equisolidproj.hdr* > *HDRfile_equidistantproj.hdr*

Besides adjusting the projection of an HDR image, the fisheye_corr.cal file also sets the pixel values outside the 180° fisheye view to 0 for all three channels, namely to black.

7. Vignetting correction

To correct the light fall-off towards the edges of an image due to the vignetting effect, the .cal text file containing the vignetting correction function corresponding to the lens aperture is used (see 2.3.5). The vignetting correction can be applied to an HDR image by using *pcomb* with the correct .cal file. The line of code to apply the vignetting correction (*vignetting_fX.cal*) corresponding to the aperture used for the input HDR image (*HDRfile.hdr*) using *pcomb* is as follows:
> pcomb -f *vignetting_fX.cal HDRfile.hdr* > *HDRfile_vignettingcorrected.hdr*

If the pixels outside the fisheye view have not been previously set to black (R, G, B = 0, 0, 0), the vignetting correction function might apply to those as well, and alter the aspect of the HDR image. This has no impact on the data contained in the fisheye view, and the pixels outside of the fisheye view can be reset to black afterwards. This black setting is not needed in case of use of *evalglare*.

8. ND filter correction

When a ND filter is used to capture a sequence of multiple exposures, the resulting HDR image needs to be corrected for the chromatic shift and the brightness scaling introduced by the filter (see 2.3.6). The correction of the ND filtered HDR image can be done with *pcomb*, which applies the three linear correction functions (one for each RGB channel) stored in the .cal text file to the pixel values. The line of code to apply the ND correction (*ND_correction.cal*) to a filtered HDR image (*HDRfile.hdr*) using *pcomb* is as follows:
> pcomb -f *ND_correction.cal HDRfile.hdr* > *HDRfile_NDfiltercorrected.hdr*

9. Photometric adjustment by spot luminance measure

HDR photography allows capturing relative luminance values of all the pixels in the lens FOV. In order to retrieve the absolute luminance values of the scene, a photometric adjustment has to be applied to the HDR image, which consists of multiplying the relative luminance values of every pixel by a scaling factor. This scaling factor is the ratio of the measured to the HDR-derived luminance value of a target in the FOV (Jacobs 2007). The

factor is believed to be dependent on the lens aperture and the type of the main lighting source, and should theoretically oscillate around 1 (Brotas and Jacobs 2006). In practice, there exist two main methods to adjust an HDR image photometry with spot luminance measures, depending on the conditions under which the HDR images are captured.

When HDR images of different scenes are recorded, it is recommended to apply a proper scaling factor to each generated HDR image (Van Den Wymelenberg 2012). The photometric adjustment therefore requires the measurement with a spot luminance meter of the luminance value of a target in the FOV, such as a mid-range gray card (Figure 15), during each capture of multiple exposures. The gray color of the target should be as neutral as possible to reflect evenly all wavelengths between 380 nm and 780 nm, and should have a mid-range reflectance to be representative of the visual scene. Mid-range gray targets have been shown to produce lower error in terms of luminance than colored, black, or white targets (Inanici 2006). Furthermore, the spot luminance measure should be done in an area of the scene with mid-range luminance values, and especially not in an area prone to lens flare or pixel overflow. Since the exact pixel coordinates of the target in the fisheye view are unknown a priori, the photometry adjustment has to be done manually, for instance through *Photosphere*. To do so, the target has first to be found on the displayed HDR image in *Photosphere* viewer. Then the calibration is automatically applied to every pixel of the HDR image by inputting the measured spot luminance value for the target area.



Figure 15. Example of a visual scene with two mid-range gray cards used as targets for spot luminance measurement.

When several HDR images are generated for the same scene under similar lighting conditions, a calibration factor can be derived for the first HDR image and applied to all subsequent images generated with the same equipment and the same lens aperture. There is therefore no need to collect a spot luminance value on a mid-range gray target in the FOV for each HDR image, but only for each first HDR image using a specific aperture.

The calibration factor corresponding to that specific aperture is then defined as the ratio of the measured to the HDR-derived luminance value of the target. The photometric adjustment is applied to the HDR image using *pcomb* with the calibration factor corresponding to the HDR image aperture. The line of code to apply the calibration factor (*K*) to an HDR image (*HDRfile.hdr*) using *pcomb* is as follows:
> pcomb -s K *HDRfile.hdr* > *HDRfile_CF.hdr*

For the example equipment, the mean calibration factors for indoor scenes with daylight as the principal lighting source were defined as 1.21 for an aperture of f/8, and 1.24 for an aperture of f/11. For indoor scene under artificial lighting, the mean calibration factor could reach 1.87 for an aperture of f/22.

10. HDR image header editing

Correct information in the HDR image header is essential for quite all post-analyses. Besides the calculation of metrics, which are generally depending on correct angular relations in the image (e.g. glare metrics), the calculation of an average value of a zone requires the consideration of the solid angle of each pixel to be mathematically exact. Since the view information stored in the header is not correct (see 2.4.3), postprocessing tools will calculate the angles (including the solid angles) incorrectly, distorting the results. For that reason, the view information has to be adjusted.

The view information in the header consists of the projection type of the lens, as well as the total viewing angle of the lens. The projection type is reported in the header as *-vta* for an equidistant projection, *-vth* for an orthographic projection, or *-vtv* for a non-fisheye lens. The total viewing angle is reported in degrees both vertically, i.e. *-vv*, and horizontally, i.e. *-vh*.

The first step to adjust the view information in the HDR image header is to erase the existing information. The line of code to erase the view entry from the header of an HDR image (*HDRfile.hdr*) using *getinfo* is as follows (under Windows, the line of code requires the GNU package "*sed for windows*" to be installed):
> (getinfo < *HDRfile.hdr* | sed "/VIEW/d" && getinfo - < *HDRfile.hdr*) > *HDRfile_withoutView.hdr*

In a second step, the correct view information has to be inserted back in the HDR image header. The line of code to set the correct view information (*"VIEW= -vt? -vv X -vh X"*) in the header of an HDR image (*HDRfile.hdr*) using *getinfo* is as follows:
> getinfo -a *"VIEW= -vt? -vv X -vh X"* < *HDRfile.hdr* > *HDRfile_correctView.hdr*

Furthermore, it was recommended in a previous step (see 2.5.4) to include the exposure value in the pixels and remove it from the HDR image header. By doing so, the header contains no exposure information, implying a default exposure value of 1.

Since an HDR image generated with the example equipment and calibrated according to the previous steps has an equidistant projection and a total viewing angle of 186°, the view information in the HDR image header is reported as "VIEW= -vta -vv 186 -vh 186".

11. Validity check

At the end of the process, each HDR image should be checked before being used as a luminance map. The reason for this is that even following strictly the described step-by-step process, there might occur unexpected significant errors in the HDR images. Therefore, especially for use in research, each HDR image has to undergo a quality check before being used. This check should also be reported when results based on HDR images are published.

There exist at least two ways for checking the validity of the luminance measurements made with HDR photography: the illuminance comparison and the luminance comparison. The illuminance check should be preferred, especially when expecting high luminance (>30,000 cd/m^2) in the HDR image (e.g. sky, sun or reflection of the sun, sun visible through shadings, etc.). While the luminance check only looks at a restricted reference area, the illuminance check considers the integral of the luminance values over the whole hemisphere and is therefore more thorough, and more appropriate to detect pixel overflow.

Illuminance comparison. The illuminance comparison checks the luminous balance to ensure that the total lighting energy embodied in the HDR image is equivalent to the total lighting energy reaching an illuminance sensor placed just above the lens. More specifically, the integration of all luminance values over the hemispheric FOV captured in the HDR image should correspond to the illuminance value measured by a properly calibrated illuminance meter placed next to the lens (Kent 2016). By positioning the illuminance meter above the fisheye lens, it is assured that, in the unfortunate situation where the lens is shading part of the illuminance meter sensor, it only shades the light reflected from the ground. On the opposite, if the illuminance meter was shading part of the fisheye view, this would be directly visible in the image.

In practice, the integration of all luminance values over the hemispheric FOV captured in the HDR image corresponds to the illuminance of the calibrated HDR image. The illuminance of the HDR image can be derived through *evalglare* and its -V option (Wienold et al. 2004), and compared to the illuminance reading of the sensor. The line of code to retrieve the illuminance value of an HDR image (*HDRfile.hdr*) using *evalglare* is as follows:

> evalglare -V *HDRfile.hdr*

When the error between the sensor-measured and HDR-derived illuminance values is larger than 25% (see 3.1) although the calibration process was conducted meticulously, it most probably means that for some areas of the HDR image, the luminance is over- or under-estimated. In the specific case where the measured illuminance value is significantly larger than the HDR-derived value and there is a very bright spot in the FOV such as the sun, the luminance underestimation might be explained by pixel overflow in the HDR image (see 2.3.6). In case pixel overflow happened in recorded images and a recapturing with an ND filter is not possible, *evalglare* offers a correction function (Wienold and Andersen 2016), and alternatives have also been proposed by Jakubiec et al (Jakubiec et al. 2016a).

Luminance comparison. An additional way of checking the validity of calibrated HDR images is to take more than one spot luminance measure in the scene when capturing the sequence of multiple exposures, especially on low- or high-range gray card placed in the dark and bright parts of the scene. These measured values can then be compared to the HDR-derived values retrievable with *ximage* or *Photosphere* for instance. The line of code to display an HDR image (*HDRfile.hdr*) using *ximage* is as follows:
> ximage *HDRfile.hdr*
Once the HDR image is displayed via *ximage*, the luminance can be retrieved by clicking on the point of interest in the HDR image viewer and typing *l* (like luminance).

For scenes in which the luminance range does not exceed 30,000 cd/m^2, one could expect less than 10% error, as it has been demonstrated in the literature (Cai and Chung 2011; Inanici 2006). However, the luminance error from HDR images of more extreme scenes cannot be extrapolated from these results, and further research is needed to define a quality threshold for luminance error of HDR images with bright light sources.

In brief, Table 3 summarizes the steps necessary to generate and calibrate an HDR image from a sequence of multiple exposures in jpeg format, as well as the material required to execute these steps, which is either measured or has been derived during the one-time setup, and the main Radiance commands.

Table 3. Summary of the steps, required material (measured or derived), and commands to generate and calibrate an HDR image from a sequence of multiple exposures in jpeg (the part of the commands written in italic text need to be adjusted to the real values)

Calibration step	Required material	Generation and calibration command (Linux)
1. Capture of exposures	/	This step can be automated through different software (qDslrDashboard, digiCamControl, etc.)
2. Selection of exposures	/	This step can be automated through different software (R, python, etc.)
3. Merging of exposures	multiple exposures + response function	hdrgen **.jpg* -o *output1.hdr* -r *camera.rsp* -a -e -f -g

4. Nullification of exposure value	/	ra_xyze -r -o *output1.hdr* > *output2.hdr*
5. Cropping and resizing	fisheye view coordinates	pcompos -x *diameter* -y *diameter output2.hdr* *-xleft -ydown* > *output3.hdr* pfilt -1 -x *xdim* -y *ydim output3.hdr* > *output4.hdr*
6. Projection adjustment	distortion function	pcomb -f *distortion.cal output4.hdr* > *output5.hdr*
7. Vignetting correction	vignetting curves	pcomb -f *vignetting.cal output5.hdr* > *output6.hdr*
8. ND filter correction	ND filter correction function	pcomb -f *correction.cal output6.hdr* > *output7.hdr*
9. Photometric adjustment	measured L_T or calibration factor	pcomb -s *factor output7.hdr* > *output8.hdr*
10. HDR image header editing	projection type + real viewing angle	(getinfo < *output8.hdr* | sed "/VIEW/d" && getinfo - < *output8.hdr*) > *output9.hdr* getinfo -a "VIEW= -*vta* -vv *angle* -vh *angle*" < *output9.hdr* > *output10.hdr*
11. Validity check	measured E_V + luminous range	evalglare -V *output10.hdr*

For the command of step 10, vta needs to be changed to vth for hemispheric projection.

3. Discussion

1. Expected range of errors

A dataset of 795 HDR images was used to evaluate the range of errors that can be expected from HDR photography and this step-by-step calibration process. This dataset was gathered during a field study conducted in four countries (Chile, Belgium, Japan, and Switzerland) from March 2017 to August 2018. 180° luminance maps containing very diverse office scenes, namely workers' FOV when sitting at their desk, were collected for the study. The study took place under clear sky conditions in different office buildings for which the main light source was daylight, and for office desks that were located next to an east-, west-, or south-oriented (north- for Chile) window. The detailed experiment protocol is available in (Pierson et al. 2017a).

The LDR images were all captured with the example equipment. The previously described step-by-step process was applied rigorously to generate and calibrate, with a proper calibration factor for each image, the 795 luminance maps. From this dataset, the mean error in terms of vertical illuminance, with the error being calculated according to

equation 11, for all luminance maps is 3.05%, and the largest error is 74.88%. Only 1.38% of the luminance maps (11 maps) showed an error of more than 25%.

$$\varepsilon_{E_v}\,[\%] = \frac{|E_{v,HDR} - E_{v,measured}|}{E_{v,measured}} * 100 \qquad (11)$$

where ε_{Ev} is the error in vertical illuminance [%];
$E_{v,HDR}$ is the HDR-derived vertical illuminance [lux];
$E_{v,measured}$ is the sensor-measured vertical illuminance [lux].

Because it is expected that luminance maps having a large range of luminance will be prone to larger errors, a detailed error analysis (Table 4) is performed separately for the luminance maps of the dataset having a maximal luminance value lower than 30,000 cd/m², and those having a maximal luminance value larger than 30,000 cd/m².

From Table 4, it is observed that the errors in vertical illuminance are larger for luminance maps having a high luminance range compared to luminance maps having a lower luminance range. In general, an error in vertical illuminance of less than 10% should be expected, and HDR images with an error of more than 25% should be rejected. The numbers given in Table 4 are derived from the absolute value of the errors, thus without considering their +/- sign. But it should be noted that a systematic positive (or negative) error in vertical illuminance should not occur. If the mean error (not in absolute terms) is not approaching zero, it means that an error causing a systematic increase (or decrease) in vertical illuminance was inserted in the calibration process.

Table 4. Vertical illuminance errors evaluated from a set of luminance maps collected with the example equipment and calibrated with the described step-by-step calibration process applying a proper calibration factor for each image.

	HDR images with L_{max} < 30,000cd/m²	**HDR images with L_{max} > 30,000cd/m²**	**All HDR images**
N	666	129	795
Mean error	2.5%	6.1%	3.1%
Maximal error	37.7%	74.9%	74.9%
HDR images with error < 25%	663 (99.6%)	121 (93.8%)	784 (98.6%)
HDR images with error < 10%	648 (97.3%)	112 (86.8%)	760 (95.6%)

Furthermore, although it is recommended to apply all the steps of the here-described calibration procedure and a proper calibration factor for each HDR image, it might happen that this procedure cannot be executed in its entirety. It is therefore interesting to know the dimensions of the error that should be expected if a specific step is not performed or if proper calibration factors cannot be derived.

Regarding the photometric adjustment of the HDR images (see 2.5.9), error statistics have been evaluated for the low- and high-range luminance maps of the dataset (Table 5), to compare the error ranges when:

- individual calibration factors (CFs) are used for each image;
- a predefined CF is used for all images with the same aperture;
- no CF is derived, and no photometric adjustment is applied.

Table 5. Comparison of vertical illuminance errors between the different photometric adjustment methods for the set of luminance maps collected with the example equipment and calibrated with the described step-by-step calibration process

	HDR images with L_{max} < 30,000cd/m²			**HDR images with L_{max} > 30,000cd/m²**		
	Individual CFs	Predefined CFs	No CFs	Individual CFs	Predefined CFs	No CFs
Mean error	2.5%	6.6%	14.5%	6.1%	12.1%	18.6%
Maximal error	37.7%	55.0%	56.0%	74.9%	131.9%	96.5%
HDR images with error < 25%	99.6%	99.4%	95.0%	93.8%	89.9%	84.5%
HDR images with error < 10%	97.3%	79.9%	23.7%	86.8%	61.2%	25.6%

As expected, the use of individual CFs provides the most accurate luminance maps in terms of vertical illuminance, while not applying any photometric adjustment causes only 25% of the luminance maps to have an error lower than 10%. However, the errors calculated for the luminance maps without any photometric adjustment are very dependent on the equipment in use, and another equipment might give a different error range.

Since the errors in vertical illuminance related to the other steps of the described process are highly dependent on the scene being evaluated, the error statistics derived from the dataset for each missing step are not reported. For instance, a dataset made of extreme scenes with very bright light sources in an off-center position most probably suffer from larger errors in vertical illuminance due to the omission of the vignetting correction than a dataset mostly made of quite uniform indoor daylit scenes.

Instead, a description of the impact that could be brought by the omission of each specific step of the process is made in Table 6. An estimation based on theoretical principles of the error due to the omission of each step is also given.

Table 6. Impact and estimated error that can be expected when one of the steps of the calibration process is not executed

Missing step	Impact	Consequence
Selection of exposures	Superfluous images used in the merging step leading to more weight given to not-properly exposed pixels	Error in luminance in the range of 0-5% for some pixels
Nullification of exposure value	Loss of exposure information of the HDR image	Error in luminance up to 100% for all pixels
Projection adjustment	Wrong calculation of angles and solid angles during HDR image post processing	Error in solid angle size up to 20% for some pixels (e.g. for equisolid-angle lenses)
Vignetting correction	Underestimation of the luminance in the outer angle ranges of the lens field of view	Depending on lens and aperture, error in luminance up to 50-60% for the pixels in the outer angle ranges
Photometric adjustment	Non-scaled relative luminance values	Error in luminance up to 100% for all pixels
Header editing: view type	Wrong calculation of angles and solid angles during HDR image post processing	Error in vertical illuminance and in metrics using angles in their equation (i.e. DGP, L_{avg}) up to 100% (e.g. when a non-fisheye view type is used for a fisheye lens)
Header editing: viewing angle	Wrong calculation of angles and solid angles during HDR image post processing	Error in vertical illuminance and in metrics using angles in their equation (i.e. DGP, L_{avg}) in the range of 0-5%

DGP = Daylight Glare Probability ; L_{avg} = average Luminance

Furthermore, it should be noted that, up to now, there exist no solutions to correct for lens flare, although several authors have acknowledged or quantified the related error (Anaokar and Moeck 2005; Inanici 2006; Rea and Jeffrey 1990). Lens flare is the radial scattering of light information of a single pixel into neighboring pixels (Figure 13), which results in a loss of luminance information of the central pixel and an increase of false luminance data in the neighboring pixels (Stanley 2016). Therefore, it should be reminded that the surrounding area of a bright light source in an HDR image is most probably prone to an error in luminance values due to lens flare.

Even when the complete calibration procedure is performed and a proper calibration factor is applied, some of the luminance maps have an error larger than 25% in vertical illuminance, which cannot be explained by pixel overflow. This is the case for

0.5% (n=4) of the luminance maps of this dataset. Up to now, this error cannot be explained and these images have to be disregarded. If an illuminance comparison check had not been conducted for every calibrated HDR images, it might have happened that these erroneous luminance maps corrupt the dataset, making the associated results misleading. This validity check is also a good way of detecting when one or several steps of the calibration procedure went wrong, causing all the luminance maps to be flawed.

2. Regarding artificial lighting studies

In the case of artificial lighting, the HDR image generation and calibration process might differ in several ways to the process described in this tutorial. The main differences and challenges that should be accounted for when creating luminance maps of artificially lit scenes are highlighted below.

When the predominant lighting type is modified, the first adaptation of the process is the modification of the white balance setting of the camera if LDR images are recorded in jpeg format. The white balance setting should be defined according to the color temperature of the studied lighting conditions. A recent study showed that, for a scene in which the predominant lighting source was fluorescent, a daylight white balance setting produced response curves with extreme abnormalities and inconsistencies whereas a cool-white fluorescent white balance setting produced very consistent response curves (Stanley 2016).

Secondly, the derivation of the response function and the predefined calibration factors, as well as the chromatic correction if an ND filter is used, should all be carried out in similar lighting conditions than the ones that will be measured.

Furthermore, other issues will have to be taken care of depending on the kind of artificial light source being measured through the HDR photography.

When light sources operated on alternating currents are the main lighting component of the scene, the flicker, which is a repetitive change in brightness of an electric light source generally invisible to the human eye due to its rapid frequency (IESNA 2000), might be one of these issues. Since multiple exposures are captured, the lighting conditions of the scene have to remain constant throughout the sequence. The flicker might therefore interfere with the recorded values during the short exposures. For instance, it has been shown that the error related to the flicker of a LED could be larger than 40% for an exposure time of 1/250s (Jacobs 2012).

To measure the flicker frequency, an oscilloscope is needed. If the flicker frequency is known or measured, the shortest exposure time should be 10 times the flicker frequency to reduce the impact of flicker to a minimum. But if the flicker frequency cannot be measured, shooting a series of 100 images with the same exposure time and fixed settings, and comparing the differences in pixel values between the images gives an

indication of the error related to the flicker that can occur for that exposure time. After repeating this procedure for different exposure times (e.g. 100 images for 1/500s, 100 images for 1/250s), the shortest exposure time can be defined according to what is acceptable as an error related to flicker.

To be on the safe side, and without measuring the flicker frequency or doing any additional tests, the following rule of thumb should be used: the shortest exposure time should be 10 times the grid-net frequency (assuming the lowest possible flicker frequency equals the electrical grid frequency). This implies that for a 50 Hz grid, the shortest exposure time should be 0.2 s (1/5 s). In this case, collecting a series of 15 under- and overexposed images requires the use of an ND filter.

Another potential issue lies with the resolution of HDR images and the size of the light source(s) being measured. For instance, current LED luminaires are designed as a juxtaposition of very small LED light sources, which could induce a contrast to the human eye depending on several factors such as the distance. However, due to its resolution still very limited compared to our own visual system, a camera might not be able to capture this contrast. Therefore, the recorded luminance distribution of the luminaire will not be representative of the human eye perception as the peak luminance of the individual LED light sources will be averaged in the pixels of the luminaire area.

These attention points do not constitute an exhaustive list, and other challenges might emerge when measuring artificially lit scenes through HDR photography with semi-professional equipment.

3. Regarding color and circadian lighting studies

The procedure detailed in this paper aims at ensuring photometric accuracy, but does not necessarily lead to colorimetric accuracy. For an application in circadian lighting or color studies, the generation and calibration of HDR images should be executed through an alternative procedure.

Jung and Inanici (Jung and Inanici 2018) recently investigated HDR photography for measuring circadian lighting. They proposed a procedure in which CIE XYZ values should first be retrieved using the standardized sRGB to CIE XYZ color transformation matrix (IEC 1999). In a second step, each channel should be adjusted with a specific calibration coefficient determined by comparing tristimulus values (XYZ values) measured with an illuminance based color meter with the triplet retrieved from the HDR fisheye image. From these color calibrated images, equivalent melanopic illuminance values could be derived. An average error of 10% and a maximum error of 16% were observed. It was concluded that HDR fisheye images (generated from a Canon EOS 5D fitted with a Sigma 8mm F3.5 EX DG) can be used to measure circadian lighting values (per-pixel equivalent melanopic luminance and illuminance values).

Alternatively, rather than making the assumption that camera sensor primaries are ITU-R BT.709 primaries and using the sRGB transform matrix for retrieving CIE XYZ values, a color transform matrix can be determined specifically for each camera/lens association (Kim and Kautz 2008).

4. Limitations

It should be noted that consumer-DSLR-cameras are no measurement tools. HDR photography has however been shown as a reliable technique to measure luminance (Inanici 2006). Therefore, the step-by-step calibration process described here can be used for typical indoor daylit scenes, although larger luminance errors could be expected for darker areas in a visual scene.

5. Conclusion

A synthetic and pragmatic overview of the step-by-step calibration process to generate a calibrated HDR fisheye image with semi-professional equipment is presented. The described process is aimed at creating measured luminance maps for daylighting studies (thus for daytime applications), although the main attention points to adapt the process for artificial and circadian lighting studies are highlighted.

All the presented calibration steps, as well as the one-time setup steps, are necessary to produce an accurate luminance map. Along the process, examples established with a Canon EOS 5D Mark II camera, a Sigma EX DG 8mm f/3.5 fisheye lens, and the *Radiance* suite of programs (Ward 1987) are given.

Besides *Radiance*, more user-friendly computer software products offer to generate and calibrate HDR images from a sequence of multiple exposures. To this date, none of the most common ones carry out all the steps described in this tutorial. For instance, *hdrscope* misses the HDR image generation, the optional ND filter correction and the projection adjustment; *Photosphere* misses the optional ND filter correction, the vignetting correction, and the projection adjustment; *WebHDR* misses the HDR image cropping, the optional ND filter correction, the vignetting correction, and the projection adjustment. Another downside of these software products is the inability of the user to fully understand the modifications applied to the images, and therefore to detect a potential error along the process.

A common pitfall of HDR calibration is the use of outdated versions of *Radiance* or any other software. Freely available software tools are constantly being tested by the community, and corrected when need be. Therefore, it is important to make sure that the version in use is the latest release, and avoid introducing problems which have already been solved in a most recent version.

Moreover, although it would allow many more people to create luminance maps through HDR photography, the use of tablets, smartphones, and any other connected devices to capture a sequence of multiple exposures is not recommended. Studies (Bieckmann 2016; Cerqueira et al. 2018) have indeed shown a lack of reproducibility with this kind of equipment, especially if updates are being installed on the device without the user knowing about it.

At last, the given examples show that a high measurement accuracy and a good reproducibility can be obtained from HDR photography with commercially available equipment when the calibration process is meticulously applied. For luminance maps with luminance values lower than 30,000 cd/m², 97% of calibrated HDR images generated with the example equipment demonstrate an error in vertical illuminance lower than 10%, against 87% for luminance maps with a higher range of luminance. However, a few calibrated HDR images still present an error in vertical illuminance of up to 75%. Some of these large errors can be explained by pixel overflow, though not all of them. The validity check based on an external measurement, such as the vertical illuminance, should therefore be mandatory for each generated luminance map in lighting research, and should be reported in related publications. Luminance maps failing the quality measure should be deleted from the evaluated dataset.

In the future, a calibration process for the HDR photography with commercially available equipment should be established for artificial lighting, road lighting, and color studies. This could be the opportunity for the lighting community to standardize the calibration process for HDR photography and define a quality criterion that should be reported and met by all lighting studies using this measurement technique.

References

Anaokar S, Moeck M. 2005. Validation of high dynamic range imaging to luminance measurement. LEUKOS. 2(2):133-144.

Anderson H. 2006. The nodal point. http://www.hugha.co.uk/NodalPoint/Index.htm [accessed 2019 January 27].

Bieckmann K. 2016. Measuring illuminance via smartphone? Paper presented at: LICHT 2016. Karlsruhe, Germany.

Brotas L, Jacobs A. 2006. Webhdr. 5th International Radiance Workshop. Leicester, UK.

Cai H, Chung TM. 2011. Improving the quality of high dynamic range images. Lighting Research & Technology. 43:87-102.

Cauwerts C. 2013. Influence of presentation modes on visual perceptions of daylit spaces [PhD dissertation]. Université catholique de Louvain (UCL).

Cauwerts C, Bodart M, Deneyer A. 2013. Comparison of the vignetting effects of two identical fisheye lenses. LEUKOS. 8(3):181-203.

Cerqueira D, Carvalho F, Melo RB. 2018. Is it smart to use smartphones to measure illuminance for occupational health and safety purposes? Paper presented at: Intl Conference on Applied Human Factors and Ergonomics. Orlando, USA.

Debevec PE, Malik J. 1997. Recovering high dynamic range radiance maps from photographs. Paper presented at: SIGGRAPH 97. Los Angeles, USA.

Dumortier D, Coutelier B, Faulcon T, Van Roy F. 2005. Photolux: A new luminance mapping system based on nikon coolpix digital cameras. Paper presented at: Lux Europa 2005. Berlin, Germany.

Geisler-Moroder D, Lee E, Ward G. 2016. Validation of the radiance 5-phase-method against field measurements. Paper presented at: 15th International Radiance Workshop. Padua, Italy.

Hirning M. 2014. The application of luminance mapping to discomfort glare: A modified glare index for green buildings [PhD dissertation]. Queensland University of Technology (QUT).

Hubai Z. 2014. qdslrdashboard. https://dslrdashboard.info/ [accessed 2019 January 17].

Ihaka R, Gentleman R. 1996. R: A language for data analysis and graphics. Journal of Computational and Graphical Statistics. 5(3):299-314.

Inanici M. 2006. Evaluation of high dynamic range photography as a luminance data acquisition system. Lighting Research & Technology. 38(2):123-136.

Jacobs A. 2012. Glare measurement with hdr photography. 11th International Radiance Workshop. Copenhagen, Denmark.

Stanley MJ. 2016. On the development and error analysis of a high dynamic range imaging system for luminance measurements [Master thesis]. University of Colorado Boulder.

Illuminating Engineering Society of North America (IESNA). 2000. The IESNA lighting handbook. New York, USA: Illuminating Engineering Society.

Inanici M. 2006. Evaluation of high dynamic range photography as a luminance data acquisition system. Lighting Research & Technology. 38(2):123-136.

Inanici M. 2009. Introduction to high dynamic range photography. 8th International Radiance Workshop. Boston, USA.

Inanici M. 2010. Evalution of high dynamic range image-based sky models in lighting simulation. LEUKOS. 7(2):69-84.

Inanici M, Galvin J. 2004. Evaluation of high dynamic range photography as a luminance mapping technique. Berkeley, USA: Lawrence Berkeley National Laboratory.

International Electrotechnical Commission (IEC). 1999. Colour measurement and management in multimedia systems and equipment. Part 2-1: Default RGB Colour Space - sRGB. Geneva, Switzerland.

Jacobs A. 2007. High dynamic range imaging and its application in building research. Advances in Building Energy Research. 1(1):177-202.

Jacobs A. 2012. Glare measurement with hdr photography. 11th International Radiance Workshop. Copenhagen, Denmark.

Jacobs A, Wilson M. 2007. Determining lens vignetting with hdr techniques. Paper presented at: Light'2007. Varna, Bulgaria.

Jakubiec JA, Inanici M, Van Den Wymelenberg K, Mahic A. 2016a. Improving the accuracy of measurements in daylit interior scenes using high dynamic range photography. Paper presented at: PLEA 2016. Los Angeles, USA.

Jakubiec JA, Van Den Wymelenberg K, Inanici M, Mahic A. 2016b. Accurate measurement of daylit interior scenes using high dynamic range photography. Paper presented at: CIE 2016. Melbourne, Australia.

Jones NL, Reinhart CF. 2017. Experimental validation of ray tracing as a means of image-based visual discomfort prediction. Building and Environment. 113:131-150.

Jung B, Inanici M. 2018. Measuring circadian lighting through high dynamic range photography. Lighting Research & Technology. 51(5):742-763.

Kent MG. 2016. Temporal effects in glare response [PhD dissertation]. University of Nottingham.

Kerr D. 2008. The proper pivot point for panoramic photography. http://dougkerr.net/Pumpkin/articles/Pivot_Point.pdf [accessed June 13, 2017].

Kim MH, Kautz J. 2008. Characterization for high dynamic range imaging. Computer Graphics Forum. 27(2):691-697.

Mantiuk R, Krawczyk G, Mantiuk R, Seidel H-P. 2007. High dynamic range imaging pipeline: Perception-motivated representation of visual content. Paper presented at: SPIE: Human Vision and Electronic Imaging XII. San Jose, USA.

Mitsunaga T, Nayar SK. 1999. Radiometric self calibration. Paper presented at: IEEE Conference on Computer Vision and Pattern Recognition. Fort Collins, USA.

Pierson C, Piderit MB, Wienold J, Bodart M. 2017a. Discomfort glare from daylighting: Influence of culture on discomfort glare perception. Paper presented at: CIE 2017 Midterm Meeting. Jeju, South Korea.

Pierson C, Wienold J, Jacobs A, Bodart M. 2017b. Luminance maps from high dynamic range imaging: Calibrations and adjustments for visual comfort assessment Paper presented at: Lux Europa 2017. Ljubljana, Slovenia.

Rea MS, Jeffrey I. 1990. A new luminance and image analysis system for lighting and vision I - Equipment and calibration. LEUKOS. 19(1):64-72.

Reinhard E, Ward G, Pattanaik S, Debevec P. 2006. High dynamic range imaging - acquisition, display, and image-based lighting. Elsevier Inc.

Robertson MA, Borman S, Stevenson RL. 2003. Estimation-theoretic approach to dynamic range enhancement using multiple exposures. Journal of Electronic Imaging. 12(2):219-228.

Stanley MJ. 2016. On the development and error analysis of a high dynamic range imaging system for luminance measurements [Master thesis]. University of Colorado Boulder.

Stumpfel J, Tchou C, Jones A, Hawkins T, Wenger A, Debevec P. 2004. Direct hdr capture of the sun and sky. Paper presented at: AFRIGRAPH. Cape Town, South Africa.

Van Den Wymelenberg K. 2012. Evaluating human visual preference and performance in an office environment using luminance-based metrics [PhD dissertation]. University of Washington (UW).

Ward G. 1987. Radiance. https://radiance-online.org// [accessed 2018 November 28].

Ward G. 1993. Findglare command (Radiance). http://radsite.lbl.gov/radiance/man_html/findglare.1.html [accessed 2017 September 27].

Ward G. 2001. Photosphere. http://www.anyhere.com/ [accessed 2019 March 1].

Ward G. 2016. Fisheye_corr.Cal file. https://www.radiance-online.org/cgi-bin/viewcvs.cgi/ray/src/cal/cal/fisheye_corr.cal [accessed 2018 November 28].

Wienold J. 2012. New features of evalglare. 11th International Radiance Workshop. Copenhagen, Denmark.

Wienold J, Andersen M. 2016. Evalglare 2.0 – new features faster and more robust hdr-image evaluation. Paper presented at: 15th International Radiance Workshop. Padua, Italy.

Wienold J, Christoffersen J. 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of ccd cameras. Energy and Buildings. 38(7):743-757.

Wienold J, Reetz C, Kuhn TE, Christoffersen J. 2004. Evalglare - a new radiance-based tool to evaluate daylight glare in office spaces. Paper presented at: 3rd International Radiance Workshop. Fribourg, Switzerland.

Wüller D, Gabele H. 2007. The usage of digital cameras as luminance meters. Paper presented at: Conference SPIE: Digital Photography III. San Jose, USA.