# Do people from different socio-environmental contexts perceive differently discomfort due to glare from daylight?

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Short title: Socio-environmental context and discomfort from glare

Received 26 April 2020; Revised 02 November 2020; Accepted

Exposure to daylight has much to offer and should be optimized to maximise its potential. In order to harvest its benefits, any visual discomfort from daylight should be anticipated and minimized. Hence, there is the need to predict discomfort from daylight glare. While more than twenty models for predicting discomfort from daylight glare have been developed, none accurately predict it. The inclusion of additional factors in the models may improve the predictions. One such factor is the socio-environmental context of the observer. This study compares the evaluations of discomfort glare from daylight for office buildings in four socio-environmental contexts; Chile, Belgium, Japan and Switzerland. The evaluations of discomfort glare, each consisting of subjective assessments and physical measurements of a view condition, were collected at the office desks of 401 participants, although only 211 responses were used in the analyses due to exclusion rules. The results do not suggest evidence of an influence of socio-environmental context on discomfort from daylight glare. In other words, the participants in this study perceived discomfort glare similarly, regardless of their socio-environmental context.

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# 1 Introduction

## 1.1. Background for Study

Exposure to light, and in particular daylight, has much to offer buildings and their occupants. Daylight exposure has been shown to boost learning and working performances,[1,2] increase visual comfort,[3] and reduce depression,[4] amongst other things. With regards to the building, daylighting enhances the aesthetics of a space[3,5] and can improve its energy efficiency.[6–8] Harvesting these benefits depends on one condition though: that daylight does not produce visual discomfort. One source of visual discomfort is the discomfort from glare. In this sudy, the term glare relates to discomfort glare, defined by the International Commission on Illumination (CIE) as a "*condition of vision which causes discomfort withoul necessarily impairing the vision of objects*"[9]. Upon experiencing discomfort from daylight glare, building occupants often use shading devices and as a result limit the amount of daylight entering the room. To harvest the benefits of daylight, visual discomfort should be anticipated and minimized, hence the need to predict discomfort from daylight glare reliably. To date, more than twenty models for predicting discomfort from daylight glare have been developed.[10] However, none of them can consistently and accurately explain the large variation between people' discomfort.[11,12] Improving current models that predict discomfort from glare remains a crucial step in moving towards optimal daylighting design in buildings.

In this context, it has been hypothesized that the prediction of discomfort from glare can be improved by including in current models additional relevant factors related to the context or to the subject.[13] Making a subjective assessment of discomfort glare requires the expression of a subjective feeling, which is most probably influenced by physiological or psychological processes, as well as contextual elements. In existing literature, twenty-five factors have been investigated for their potential influence on discomfort from glare, besides the six factors currently used in discomfort glare models.[12] Among these factors is the socio-environmental context of the subject, defined here as the climate and habitat (interior and exterior) to which a person has acclimatised and their behaviour and expectations towards these elements. Although a widely accepted definition of the term socio-environmental does not exist, the term is used extensively. 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. "Socio-environmental context" was chosen over "country" or "background" since these terms are more 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. As expressed in this definition, a period of acclimatization is required for the subject to be considered as part of a specific socio-environmental context. According to the U-curve of the acclimatization theory,[14,15] it takes at least two years of living in a specific context for a person to become acclimatized to that socio-environmental context.

## 1.2. Review of the Literature

The socio-environmental context of a subject is especially intriguing because while the literature suggests that it could influence discomfort from glare,[12] until recently no study has been specifically designed to investigate it.

The first observation supporting the influence of the socio-environmental context was made in 1964 by Ichikawa and Chonan[17] who reproduced in Japan the original study of Luckiesh and Guth.[16] The results of their study indicated that the arithmetic mean of the luminance of a glare source corresponding to the Borderline between Comfort and Discomfort (BCD) for the Japanese participants was 9,946 cd/m$^2$, whereas the arithmetic mean in the original study, thus for (most probably) North American participants, was 3,053 cd/m$^2$. These initial results show a much higher tolerance towards glare from Japanese participants.

Thereupon, other observations were made that suggest an influence of the socio-environmental context on discomfort from glare, always by comparing the results of two relatively similar discomfort glare studies. In Table 1, the studies of which the results have been compared are listed by pair. The most recent study in each pair, in which the comparison

of the results was described, suggests an influence of the socio-environmental context on discomfort from glare, as shown in the column “Conclusion”.

**Table 1**. Information about each pair of studies, in which the most recent one suggests an influence of socio-environmental context on discomfort from glare; in the table, BCD stands for Borderline between Comfort and Discomfort and GSV for Glare Sensation Vote

| Pair | Reference | Date | Number of participants | Assumed socio-environmental context | Conclusion |
|---|---|---|---|---|---|
| 1 | Luckiesh & Guth[16] | 1949 | 50 | North American | The average BCD brightness was higher for the Japanese participants than for the North American participants[17]. |
| | Ichikawa & Chonan[17] | 1964 | 15 | Japanese | |
| 2 | MacGowan *et al*.[18] | 1988 | ? | North American | There was a greater sensitivity to discomfort glare for the Slovak participants than for the North American participants[19]. |
| | Subova *et al*.[19] | 1991 | 32 | Slovak | |
| 3 | Petherbridge & Hopkinson[20] | 1950 | 6 | British | The GSV was higher for the Japanese participants than for the British participants[21]. |
| | Iwata *et al*.[21] | 1992 | 40 | Japanese | |
| 4 | Iwata *et al*.[21] | 1992 | 40 | Japanese | The luminance levels corresponding to Hopkinson multi-criterion scale were higher for Japanese participants than for Slovak participants[22]. |
| | Pulpitlova & Detkova[22] | 1993 | 57 | Slovak | |
| 5 | Tokura *et al*.[23] | 1996 | 240 | Japanese | The GSV was lower for the Dutch participants than for the Japanese participants[24]. |
| | Iwata et al.[24] | 1998 | 40 | Dutch | |
| 6 | Hopkinson[25] | 1971 | ? | British | The Korean participants experienced a severe discomfort glare at the DGI value of 34 whereas the Caucasian participants experienced it at 30[26]. |
| | Lee & Kim[26] | 2007 | 42 | Korean | |

Two recent studies were specifically designed to investigate the influence of socio-environmental context on discomfort from glare, namely with an identical methods for two different groups of participants.[27,28] Hence, these studies do not rely on a comparison of the results of different studies as was done previously (Table 1). The results of the study from Ko and Choi showed a higher tolerance to discomfort glare for Korean participants than for Caucasian participants, although there were only 8 Caucasian participants against 168 Korean participants. The results of the study from Iwata did not suggest a significant difference in discomfort from glare between the Middle Eastern and Japanese participants; note, however, that it was not mentioned whether the Middle Eastern participants had adequate time to acclimate to the Japanese socio-environmental context in which they were currently living.

In addition, perceptions of other environmental elements, such as thermal comfort or lighting preferences, have been shown to be influenced by the subject’s socio-environmental

context,[27,29–35] although one recent study on the visual perception of architectural spaces did not find any differences between Greek and Swiss participants.[36]

Finally, it appears that a higher percentage of people report discomfort glare in their usual work environment for the North American context in comparison to the Asian context at around 60%[37] and 20%[38] respectively. However, this data is only available in two field studies and should be interpreted with care.

### 1.3. Aim of Study

This review of literature suggests an influence of socio-environmental context on discomfort from glare. More specifically, Asian people appear less sensitive to discomfort glare than North American people, who in turn, appear less sensitive than European people.

However, most of the studies suggesting an influence of socio-environmental context on discomfort from glare have developed this hypothesis from a comparison of their results with those from previous studies. Few studies have intentionally tested the difference in discomfort from glare between different socio-environmental groups following a unique experimental protocol developed for this purpose.

For this reason, the question that this study aims to answer is: "*Does the socio-environmental context of a subject influence her/his discomfort from daylight glare in office buildings?*". The experimental design of the proposed study has been established in order to answer this research question, and potentially improve the prediction of discomfort from daylight glare. This experimental design was conducted as a field study on discomfort glare with 401 office workers in four different socio-environmental contexts.

## 2 Method

### 2.1. Study Design

A field study was conducted in four different socio-environmental contexts. Point-in-time evaluations of two view conditions were collected for each test participant in each socio-environmental context. After applying selection rules to filter out inappropriate or unreliable evaluations, the influence of the socio-environmental context was then investigated by comparing the remaining evaluations between the socio-environmental groups.

A subjective assessment made by the participant (via a digital questionnaire) and physical measurements were collected for each view condition. The physical measurements included a luminance map of the view condition generated through High Dynamic Range (HDR) photography, from which various discomfort glare metrics were later derived. Both the subjective assessment and physical measurements were gathered to compare the evaluations of view conditions between each socio-environmental context. While ideally the subjective assessment and the measurement of the view condition should be made at the *exact* same location and time, this study collected the measurement of the view condition directly after the subjective assessment, at the exact same location.

A field study was chosen over a laboratory study to refrain from having to recreate the same office-like laboratory cell in different parts of the world, to prevent subjective assessment bias due to an unfamiliar environment,[39] and to limit the experimenter's organizational load whilst abroad. It was decided that the study would take place directly in the participants' offices with on-site evaluations of the view conditions.

### 2.2. Socio-Environmental Contexts

The main criteria in selecting participants representative of different socio-environmental contexts were the environment, more specifically the climate and habitat, in which these participants were living, as well as the culture, more specifically the behaviour and expectations relative to that environment, of these participants; as per the definition. Finding people from different socio-environmental contexts in the same location proved to be unachievable, especially since people acclimatized to their surrounding context after a certain period of time.[15,40,41] The participants were therefore recruited in four different countries, and the investigator travelled to these countries to conduct the study.

Based on the literature reviewed above, it was necessary to investigate the difference between Japanese and European/Caucasian participants. Furthermore, it was decided to extend the comparison to at least one other context that had not been investigated in the literature. Overall, the four countries were chosen in order to benefit, in each context, from the help of a local research team in daylighting to set up the study. The four socio-environmental contexts compared in this study are the Chilean (CL), Belgian (BE), Japanese (JP), and Swiss (CH) contexts.

To reflect different climatic conditions in one socio-environmental context, the field study was conducted in three different cities in Chile. However, the limited sample size in each city did not allow to investigate whether the perceptions in these three locations differed. The three samples were therefore analysed as one socio-environmental context. As a result, this grouping could have mitigated in some ways the discomfort from glare in the Chilean context. As observed in Figure 1, the global horizontal illuminance representing the outdoor lighting conditions differs between these three Chilean cities.

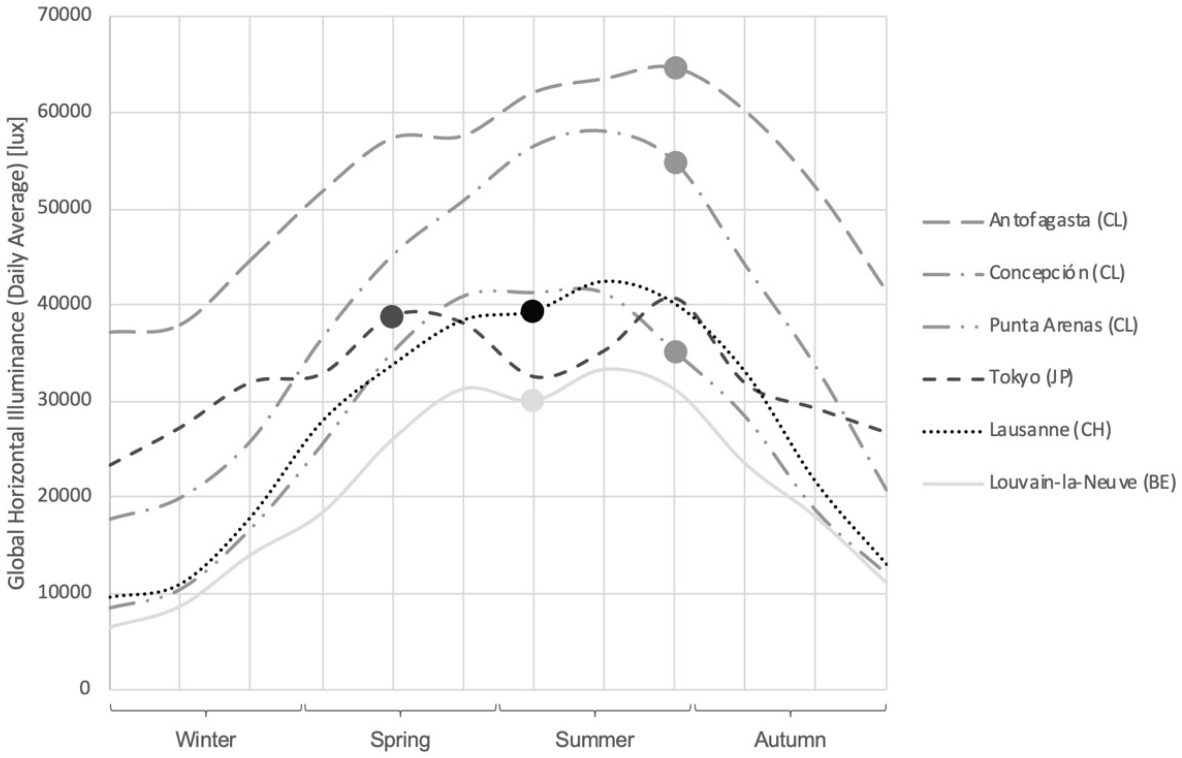



**Figure 1**: Global horizontal illuminance, expressed as a daily average for each month, in each city where the study was conducted; the dots represent the month during which the study was conducted in each context

### 2.3. Office Buildings

The field study was conducted within office buildings located in cities in four countries as described in Table 2.

**Table 2**: Description of the locations and periods during which the field study was conducted

| Socio-environmental context | City | Geographical location | Period of time |
|---|---|---|---|
| CL | Concepción | 36°49’12’’S – 73°2’40’’W | 6-12/03/2017 |
| | Punta Arenas | 53°9’17’’S – 70°54’41’’W | 13-19/03/2017 |
| | Antofagasta | 23°38’60’’S – 70°2’40’’W | 20-26/03/2017 |
| BE | Louvain-la-Neuve | 50°40’12’’N – 4°36’36’’E | 15/06-31/08/2017 |
| JP | Tokyo | 35°39’10’’N – 139°50’22’’E | 07-25/05/2018 |

In Chile, the study took place in four 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. For all the represented buildings, desk stations selected for the study were located in both open-plan and individual office spaces.

### 2.4. View Conditions

Selection criteria were established for the desk stations where the study would be conducted to limit the variations in the evaluated view conditions in order to provide a fair basis of comparison between the four socio-environmental contexts. To maximize the probability of encountering glare from daylight in real environments, only desk stations located within approximately five meters from a West-, East-, or South-oriented (North-oriented for Chile) window were considered in the study. In the data cleansing phase, all the evaluations for which the view condition did not include a window having a solid angle larger than 0.01 sr were discarded.

Furthermore, the study was conducted during the summer (Table 2) under clear sky conditions only. This allowed avoidance of clouds and variation in light levels during the evaluation of discomfort glare, and any potential seasonal bias.

Examples of a typical view condition in each socio-environmental context are given in Figure 2.

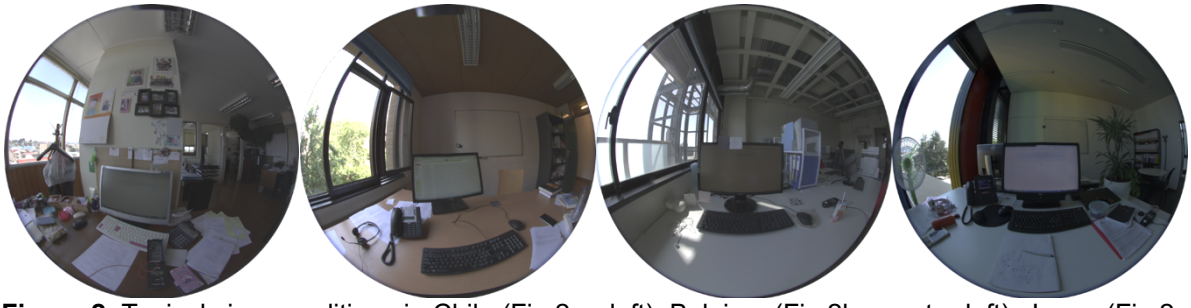


**Figure 2**: Typical view conditions in Chile (Fig.2a - left), Belgium (Fig.2b - center-left), Japan (Fig.2c - center right), and Switzerland (Fig.2d - right)

### 2.5. Participants

The participants consisted of typical office workers surveyed at their own desk station in the studied buildings of each socio-environmental context. Not all desk stations were selected in this study, hence only the office workers of the selected desk stations were considered.

The minimum required sample size in each socio-environmental context was estimated through the software G*Power 3.1.[42] For the estimation, it was assumed that the main statistical analysis would be a two-tailed logistic regression, that a Type I error rate of 0.05 and a power of 0.8 would be suitable.[43,44] From the literature, the probability of perceiving discomfort due to glare in office buildings is around 60% in Western countries[37] and around 20% in Asian countries.[38] Although this difference seems quite large and should be validated by additional field studies, this was the only available information on discomfort glare probability in the field and therefore used to evaluate the minimum required sample size in this study.

The minimum sample size to compare discomfort from glare between two contexts was estimated at 49 with this method. This means that a minimum of 98 evaluations was required in total for the four contexts to be compared. Since each participant would make only one

point-in-time evaluation of the view condition in her/his office (not counting the training evaluation), at least 25 participants in each socio-environmental context were required. Due to the large difference in probabilities assumed in this sample size evaluation, it was decided to aim for a larger sample size.

In total, 401 participants took part in the study in the four contexts. After cleansing the data (section 2.8), 211 participants remained, with a minimum of 40 participants in each context. The demographics of the final samples are described in Table 3 for each socio-environmental context.

**Table 3**: Demographics of the four final samples used to compare discomfort from glare between the four socio-environmental contexts

| Socio-environmental context | Size N | Natives [%] | Gender Men – Women [%] | Age Min – Mean (SD) – Max [y] |
|---|---|---|---|---|
| CL | 44 | 100 | 50/50 | 28 – 44 (9) – 67 |
| BE | 43 | 79 | 35/65 | 24 – 39 (12) – 73 |
| JP | 67 | 90 | 64/36 | 21 – 34 (12) – 64 |
| CH | 57 | 46 | 61/39 | 17 – 37 (11) – 61 |

### 2.6. Procedure

The participants were recruited according to their availability on the day of the study in their office, during working hours. A single session of the study lasted around 15 minutes, and the investigator was present during the entire session for each participant to ensure that the protocol was always the same. The session consisted of four main parts:

- Part 1: introduction of the study
- Part 2: evaluation of the first view condition, namely in the original lighting conditions in which the participant was working when the session started
- Part 3: gathering of information about the participant profile
- Part 4: evaluation of the second view condition, namely in lighting conditions that maximize the potential for discomfort glare from daylight

More specifically, one session unfolded as shown in Figure 3.

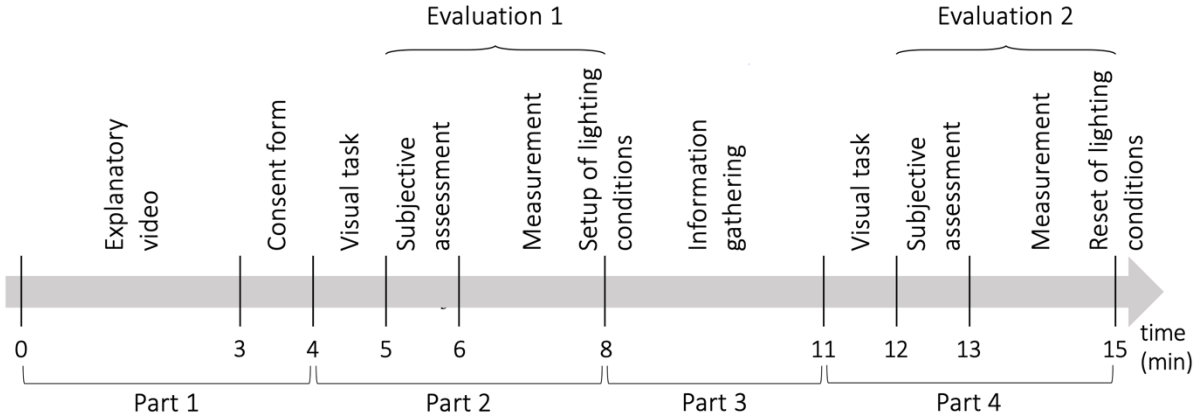



**Figure 3**: Timeline of one session of the field study

The introduction of the study consisted of a three-minute explanatory video (recorded in each of the four languages) describing the general procedure of the session, and the consent approval. The exact same information was therefore given to each participant.

The reason to make a first evaluation in original conditions was to alleviate the imposition of lighting modification for the participant, and to serve as a training for the subjective assessment. The data from this first evaluation was not used in the final analyses.

Just after this first evaluation, the lighting conditions would be modified to maximize the potential for discomfort glare from daylight by switching off electric lighting when possible and

opening the window blinds if they had previously been closed. The participant would adapt to the new lighting condition while answering the part of the questionnaire where additional information was gathered. This information primarily assessed other potentially influencing factors,[13] namely the participant's gender, age, chronotype, self-assessed glare sensitivity, visual acuity, iris pigmentation, physical state, emotional state, fatigue, caffeine ingestion, and attractiveness of the view through the window.

The subjective assessment and measurement of the second view condition would be collected at the end of the session. Only this second evaluation is considered in the analysis, the first one being used as training.

Each participant therefore provided two evaluations of their view; one under original lighting conditions, and one under maximized daylight conditions. Figure 4a shows that the original lighting conditions, hence the conditions in which the participant was working when the investigator entered the room, were similar between the four socio-environmental contexts with a median vertical illuminance at eye level of around 454 lux. As expected, the median vertical illuminance at eye level was on average higher (around 791 lux) for the second evaluation under maximized daylight conditions. The variation of the lighting conditions within each context was also larger during the second evaluation, as seen in Figure 4b.

This procedure and the questionnaire were approved by the Comité d'Ethique Hospitalo-Facultaire Saint-Luc UCL (ref: PEX-SUDGICA-01).

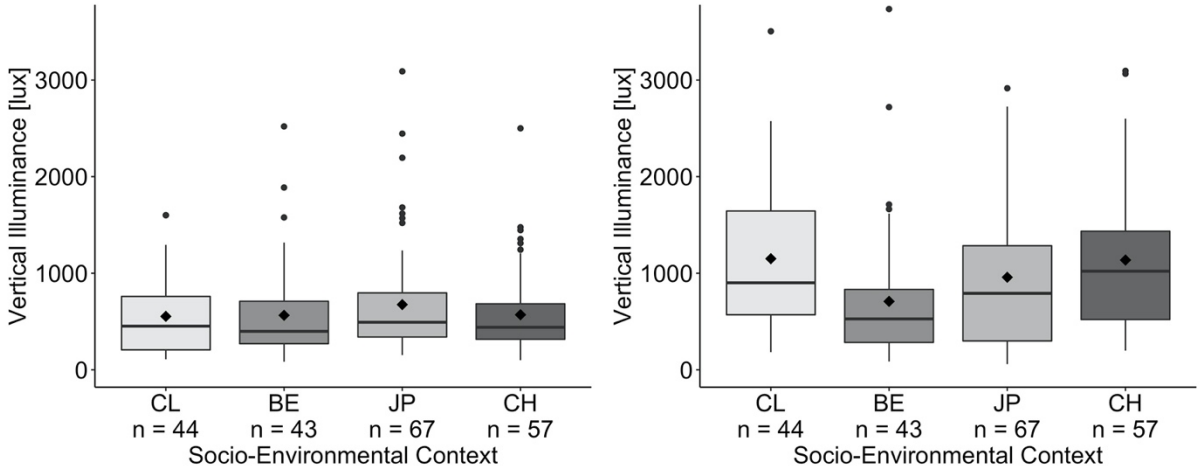



**Figure 4**: Distribution of the vertical illuminance at eye level during the evaluation of the first (Fig.4a - left) and second (Fig.4b - right) view conditions in each socio-environmental context

### 2.7. Collected Data: Questionnaire

Both the subjective assessment of a view condition, collected via a questionnaire, and its physical measurement, expressed by the discomfort glare metrics derived from the luminance map generated through HDR photography, were required to study discomfort from glare. Furthermore, demographic data of the participants, also collected via questionnaire, were needed to compare the samples in the four socio-environmental contexts and ensure their similarity.

A questionnaire was created with the open-source survey software LimeSurvey (version 2.00+) to collect information about each participant's profile, and their subjective assessment of the two view conditions (original conditions and maximized daylight conditions). The collected data was hosted on the server of UCLouvain in Belgium. Furthermore, the questionnaire had to be translated in the main language of each socio-environmental context. For this purpose, we applied a three-step procedure to minimize semantic differences between the different language versions: firstly, a translation from the original questionnaire in English to the desired language by a fluent translator; secondly, a correction of the first translation by another fluent translator; thirdly, a translation from the translated questionnaire in the desired language back to English by yet another fluent translator. If the translation back to English did

not match the original version in English of the questionnaire, the translated questionnaire was adjusted. In this way, the questionnaire was translated from English into French, Japanese, and Spanish (Table 4). The questionnaire was designed so that it leads the participant through all the steps of the session. It was completed by the participant sitting at her/his desk from her/his personal computer (Fig. 5a).

As shown in Figure 3, after being introduced to the study, the participant started the questionnaire with a visual task to ensure that he/she was working on the computer screen. The visual task presented 3 series of 6 Landolt rings oriented in 4 different ways, namely left, right, up, and down.[45] The participant had to locate the orientation of the opening of each ring, and the difficulty was increased between each series by decreasing the size of the rings.

The participant then made an assessment of the first view condition in the original lighting setting. Although four different questions (and response options) were implemented in the questionnaire to collect the subjective assessments of the view conditions regarding discomfort glare, only two questions were used for the data analysis (Table 4). The first question was about the satisfaction with the current lighting conditions. If the participant was not totally satisfied, a conditional Open-Ended Question (OEQ) followed for the participant to mention the bothering element(s). In the data processing phase, the answers to the OEQ were categorized according to two variables, i.e., “what is bothering?” and “why is it bothering?”, in order to detect the answers related to discomfort glare from daylight and transform them to a binary variable (no glare report – glare report). The OEQ answer classification was tested against the answers on 4-point scales and showed similarity.[12]

The second question asked directly whether discomfort due to glare was felt by the participant, and a short description of glare was given. The participant could answer on a 4-point glare rating scale[37]. This scale has the characteristics of having a “No/Yes” binary classifier, allowing to clearly discriminate between “no glare” and “glare” situations, and a common descriptive term at the four response points, namely “discomfort”, limiting space for interpretation.

The two additional questions implemented in the questionnaire to collect the subjective assessments regarding discomfort glare related to two other glare rating scales.[46,47] The four questions were not randomized in order not to bring the participant’s attention to glare before using the first method with the OEQ.

Furthermore, a multiple-choice question was asked to the participants who had previously reported some discomfort to detect whether the perceived discomfort was linked to daylight. The evaluations for which discomfort was reported as being caused by the computer screen or the electric lighting were discarded since these types of visual discomfort are not in the scope of this study and cannot be evaluated by daylight discomfort glare metrics.

**Table 4**: English, French, Japanese, and Spanish translations of questions 1 and 2 related to the subjective assessment of the view condition

| Q. | English | French | Japanese | Spanish |
|---|---|---|---|---|
| **1** | *At the moment, are you satisfied with the lighting conditions in your office?* | *En ce moment, êtes-vous satisfait(e) des conditions lumineuses dans votre bureau ?* | *現在、あなたはオフィスの光環境に満足していますか？* | *¿En este momento, está satisfecho(a) con las condiciones de luz en su oficina ?* |
| | □ *Unsatisfied* | □ *Insatisfait* | □ *不満* | □ *Insatisfecho* |
| | □ *Rather unsatisfied* | □ *Plutôt insatisfait* | □ *どちらかといえば不満* | □ *Más bien insatisfecho* |
| | □ *Rather satisfied* | □ *Plutôt satisfait* | □ *どちらかといえば満* | □ *Más bien satisfecho* |
| | □ *Satisfied* | □ *Satisfait* | □ *満足* | □ *Satisfecho* |
| | *(If not “Satisfied”) Which element(s) bother(s) you in the* | *(If not “Satisfait”) Quel(s) élément(s) vous dérange(nt) dans* | *(If not “満足”) 現在の光環境で、何か問題がありますか？* | *(If not “Satisfecho”) ¿Qué elementos le molestan en las* |

| | | | | |
|---|---|---|---|---|
| | *current lighting conditions?* | *les conditions lumineuses actuelles ?* | | *condiciones actuales de iluminación ?* |
| **2** | *At the moment, do you feel discomfort due to glare?* | *En ce moment, ressentez-vous une gêne due à l'éblouissement ?* | *現在、グレアによる不快感を感じますか？* | *¿En este momento, tiene molestias por deslumbramiento ?* |
| | □ *No, no discomfort* | □ *Non, pas de gene* | □ *いいえ、不快ではありません。* | □ *No, ninguna molestia* |
| | □ *Yes, a small discomfort* | □ *Oui, une faible gêne* | □ *はい、少し不快です。* | □ *Sí, un poco de molestia* |
| | □ *Yes, a moderate discomfort* | □ *Oui, une gêne modérée* | □ *はい、ある程度不快です。* | □ *Sí, una molestia moderada* |
| | □ *Yes, a large discomfort* | □ *Oui, une gêne importante* | □ *はい、とても不快です。* | □ *Sí, una molestia significativa* |

After the first subjective assessment, the participant had to answer the longest part of the questionnaire about her/his profile. First, the acclimatization of the participant to the socio-environmental context was checked through a few questions. This information was used in the data cleansing phase to discard the evaluations of the participants who had not been living in the country where the study was taking place during the last two years. Demographic information, physiological, and psychological characteristics of the participant were also gathered through the questionnaire at this point.

The questionnaire ended with a second visual task followed by a subjective assessment of the second view condition under maximized daylight conditions, as described above. Without considering the physical measurements of the view conditions taken in between the different parts of the questionnaire, the questionnaire took around six to seven minutes to complete. The full questionnaire in English is available in the Supplementary Materials 1. All the data collected was anonymized for confidentiality.

### 2.8. Collected Data: Light Measurements

In a field study, it is expected that the view conditions evaluated by the participants are all different, resulting in different stimuli. To analyze and compare the subjective assessments of these view conditions, the discomfort glare stimulus present in each view condition has to be measured. Up to now, the best way of defining a discomfort glare stimulus has been through the discomfort glare metric values. Besides the data collected through the questionnaire, measured data was therefore required to determine the discomfort glare metric values corresponding to each evaluated view condition, as well as the stability of the lighting conditions during each evaluation.

The discomfort glare metric values corresponding to a view condition can be calculated from a luminance map of that view condition. Luminance maps are images in which each pixel represents the luminance of the corresponding portion of the captured field of view.[48] To generate these luminance maps, HDR photography was used. HDR photography captures multiple exposures of a scene from an identical point of view and merges them in order to obtain an image with a higher range of luminance levels, namely an HDR image. Spot luminance and vertical illuminance measurements taken simultaneously to the sequence of multiple exposures were also collected to calibrate and check the HDR images. The equipment and procedure applied to generate the 180° luminance maps of the view conditions are described in another publication.[49] The measurements to generate a luminance map of the view condition were collected from the standard location of the participant when sitting at her/his desk (Fig. 5b).



**Figure 5**: Example of the setup of the study taking place in a real office with the participant answering the questionnaire (Fig.5a - left) and the investigator taking physical measurements of the view condition (Fig.5b - right)

Unstable lighting conditions could have made the view condition evaluated by the participant change before the physical measurements were captured. To prevent this, the stability of the lighting conditions was checked through the maximum deviation in horizontal illuminance (Equation 1) for each evaluation. 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 participant's desk and remotely controlled by a computer to record horizontal illuminance measurements during each evaluation.

$$E_{h,max,dev} = \begin{cases} 100 \cdot \frac{\min(E_h) - med(E_h)}{med(E_h)} & if\ |\min(E_h) - med(E_h)| \geq (\max(E_h) - med(E_h)) \\ 100 \cdot \frac{\max(E_h) - med(E_h)}{med(E_h)} & if\ |\min(E_h) - med(E_h)| < (\max(E_h) - med(E_h)) \end{cases} \quad \text{Eq. 1}$$

where:

$E_{h,max,dev}$ is the maximum deviation in horizontal illuminance during one evaluation [%]
$med(E_h)$ is the median horizontal illuminance during one evaluation [lux]
$min(E_h)$ is the minimum horizontal illuminance during one evaluation [lux]
$max(E_h)$ is the maximum horizontal illuminance during one evaluation [lux]

### 2.9. Data Processing

The data collected was first processed to have the information in the most relevant format for the analyses. Therefore, the discomfort glare metric values corresponding to each view condition were calculated from the luminance map of the scene through the Radiance-based program evalglare.[47] As recommended in a recent study on evalglare parameters,[50] the task area method with a factor 5 was chosen as the principal glare source detection method for the evalglare algorithm since only desk positions located close to a window were investigated, resulting mainly in saturation glare. Due to the partial inclusion of a glare source in the task area for 137 luminance maps, the glare source detection method for these luminance maps was modified to the threshold method with a threshold of 2000 cd/m$^2$. Four discomfort glare metrics, namely the CIE Glare Index (CGI), the Daylight Glare Index (DGI), the Mean Luminance ($L_{mean}$), and the Daylight Glare Probability (DGP) were calculated by evalglare and were used for the statistical analyses, together with the measured Vertical Illuminance ($E_v$). Each statistical test was therefore performed on the five metrics independently. These five metrics were selected for analysis based on their performance and robustness according to a recent cross-validation study[10] and their ability to represent the variance in the collected data according to a principal component analysis.[12]

The data was then cleansed to keep only appropriate and reliable information. To ensure stable lighting conditions, all evaluations with a maximum deviation in horizontal illuminance larger than 25%, or a deviation in vertical illuminance (between the measurement taken before and after the multiple exposures) larger than 15%, were discarded (rule 1). To avoid inaccurate

measurements, all evaluations for which the luminance map had a relative error in vertical illuminance larger than 10% were discarded, as well as evaluations for which one of the three series of the visual task scored less than 50% (rule 2). To ensure that the view conditions were comparable, all evaluations with a window located in the visual field of the luminance map resulting in a solid angle less than 0.01 sr, or with a distance between the desk and the window greater than 5 m, were discarded (rule 3). The evaluations for which discomfort glare from electric lighting or a computer screen, and not from daylight, was reported were also discarded (rule 4). Moreover, a few evaluations for which the luminance map had the sun directly in the field of view were discarded (rule 5), as these would act as outliers in the statistical analyses and are generally related to disability glare instead of discomfort glare. As a final filter, the evaluations of the participants who had not been living in the country where the study was taking place during the last two years were also discarded (rule 6). Non-acclimatized participants had to be excluded from the dataset to avoid confounding a potential effect of the socio-environmental context. However, the statistical analyses presented in section 3 were repeated with the inclusion of the non-acclimatized participants and showed very similar results. These results of these additional analyses are available in the Supplementary Materials 3.

In the end, 190 evaluations (47%) were removed from the original dataset as detailed in Table 5. The resulting dataset used for the statistical analyses contains therefore 211 evaluations (Table 3).

**Table 5**: Number of evaluations discarded for each data cleansing rule; some evaluations were discarded due to more than one rule, which means that the total sum of evaluations discarded does not correspond to the sum of evaluations discarded by each rule

| Data cleansing rule | Number of evaluations discarded (out of 401) |
|---|---|
| 1 | 46 |
| 2 | 14 |
| 3 | 77 |
| 4 | 59 |
| 5 | 10 |
| 6 | 38 |
| All together | 190 |

### 2.10. Statistical Analyses

From the literature referenced in Table 1, it is implied that participants acclimatized to different socio-environmental contexts have different sensitivities towards discomfort glare from daylight. It is not clear, however, which socio-environmental groups are more sensitive than others. As the difference in discomfort from glare between two socio-environmental contexts could have two possible outcomes, more or less discomfort, two-tailed tests are used in the statistical analyses where a significance level of 0.05 is assumed. A significance level of 0.05 means there is a 5% risk of rejecting the null hypothesis when it is true.[51] However, since each statistical test is performed for each of the five discomfort glare metrics, the significance level has to be corrected for multiple testing.[52,53] By applying a Bonferroni correction, the significance level used in the following analyses is 0.01 ($\alpha < 0.01$* for statistical significance; $\alpha < 0.002$** for statistical high significance; and $\alpha < 0.0002$*** for statistical very high significance). All the graphs presented in section 3 are based on the DGP, since this was the best performing and most robust discomfort glare metric according to a recent cross-validation study.[10] The graphs for the four other metrics are available in the Supplementary Materials 2.

The three main statistical methods that are used to analyze the collected data are the Spearman's rank correlation, the Receiver Operating Characteristic (ROC) curve analysis, and the logistic regression analysis.

The Spearman's rank correlation is the nonparametric equivalent of the Pearson's correlation. It evaluates the correlation between two variables using the rank of the data instead of their raw value, which is required for ordinal data such as subjective assessments made on glare rating scales. In this study, the results of Spearman's rank correlation are

compared to the benchmarks proposed by Ferguson:[54] $\rho > 0.2$ means a practically significant effect; $\rho > 0.5$ means a moderate effect; and $\rho > 0.8$ means a strong effect.

The ROC curve of a prediction model proposing a binary classifier system, such as the DGP metric and its cut-off values (0.35 for the borderline between imperceptible and noticeable glare; 0.40 for the borderline between noticeable and disturbing glare; 0.45 for the borderline between disturbing and intolerable glare) is a plot of the True Positive Rate (TPR) and the True Negative Rate (TNR) of a range of cut-off values. The ROC curve, for which each point corresponds therefore to a different cut-off value, illustrates the ability of the model to discriminate between two outcomes. The most common method to analyze the ROC curve of a prediction model is to evaluate the Area Under the Curve (AUC). The larger the AUC, the better the model as the TPR and TNR are maximized. In this study, the ROC curve is analyzed according to AUC benchmarks found in the literature:[55,56] $AUC < 0.6$ means a failing model; $0.6 \leq AUC < 0.7$ means a poor model; $0.7 \leq AUC < 0.8$ means an acceptable model; and $AUC \geq 0.8$ means an excellent model.

At last, a common method to describe the relationship between a binary dependent variable and an independent variable is the logistic regression model. In this study, a multiple logistic regression model is used for the multiple independent variables: each discomfort glare metric and the socio-environmental context, and one binary dependent variable, namely the binary glare report derived from the OEQ. The Wald test and the Likelihood Ratio Test (LRT) are two different statistical tests applied to assess whether one of the independent variables of the model influences, in a statistically significant way, the dependent variable. Both tests establish whether there is a relationship between the independent and dependent variables, but the Wald test does it by dividing independent categorical variables into several independent binary variables, whereas the LRT does it directly for all types of independent variables.

## 3 Results

To analyse whether there is a significant difference in discomfort from glare between the four socio-environmental contexts (section 3.3), we first need to ensure the comparability of the four socio-environmental groups (section 3.1). This is necessary due to the variation in stimuli that the participants had to assess. Then, the applicability of the existing discomfort glare metrics needs to be checked in each socio-environmental context (section 3.2). These metrics indeed serve as the basis for the following tests.

### 3.1. Comparability of the Groups

To investigate the difference in discomfort from glare between several socio-environmental groups, it is necessary these groups be comparable. Although the visual stimulus is accounted for in almost all the following analyses, the four socio-environmental groups should have relatively similar distributions of the visual conditions to be accurately compared. Furthermore, since many additional factors could impact discomfort from glare,[13] a fair basis of comparison has to be ensured regarding these factors, in order to reduce the risk of extraneous variables confounding the results. These other factors include subject-related variables, namely the gender, age, self-assessed glare sensitivity, handedness, optical correction, iris pigmentation, chronotype, caffeine ingestion, physical state, emotional state, and fatigue, but also environmental variables, namely the air temperature in the office, the attractiveness of the view through the window, and the time of day when the study occurred.

Because the participants and their office were randomly selected between the view conditions that matched the selection criteria, it is expected that the distributions of the visual conditions and most additional factors are relatively similar between the four socio-environmental groups. Descriptive statistics of these variables are visually analyzed to check for large imbalance between the four groups due to critics in the literature for the use of balance tests.[57–59] The distributions of the visual conditions, as described by the vertical illuminance at eye level in Figure 6a, are relatively balanced between the four socio-environmental contexts, besides slightly lower illuminances in the Belgian context. Furthermore, the distributions of the additional factors are generally balanced, except for three

factors. The iris pigmentation of the participant, the chronotype, and the attractiveness of the view through the window, seem to require a more thorough analysis, as an imbalance can be visually detected in Figures 6b, 6c, and 6d.

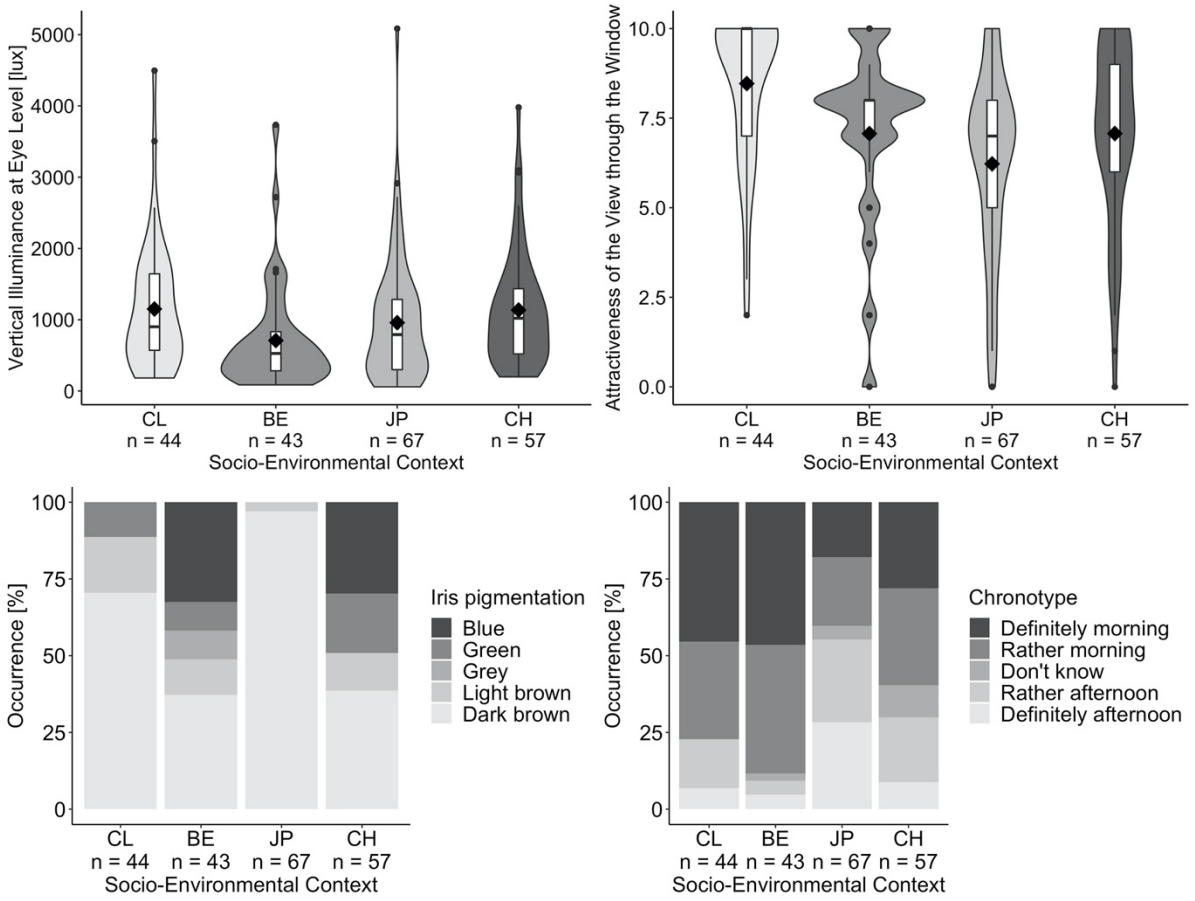



**Figure 6**: Box plots on top of violin plots, representing respectively the distribution and density of the data in each context for the vertical illuminance at eye level (Fig.6a – top left) and the attractiveness of the view through the window (Fig.6b – top right); bar plots represent the distribution of the data in each context for the iris pigmentation (Fig.6c – down left) and the chronotype (Fig.6d – down right) of the participant

Regarding iris pigmentation, the Chilean and Japanese contexts have a much larger proportion of dark-colored eye participants than the European contexts. This imbalance is an inherent (genetic) characteristic of the natives in each context and is identical to the imbalance existing between the four populations. Indeed, the distributions of the participants' iris pigmentation for the two European countries and Japan align with the distributions available in the literature for these respective areas,[60] whereas the distribution for Chile compares with a distribution published for Buenos Aires.[61]

Regarding chronotype, the imbalance 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, might be induced by a specific lifestyle or by some environmental factors, and therefore be intrinsic to a specific socio-environmental context.[62–64]

At last, regarding the view through the window, Chilean participants appear more satisfied with the view through their window than other participants. This imbalance is most likely related to the selection of the office buildings. The buildings the investigator had access to in Chile were imposing buildings located in areas where other office buildings had relatively few stories, leading to unobstructed view for the occupants. In comparison, 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 fewer unobstructed views through the window.

Although the literature is inconclusive on the influence of these three variables on discomfort from glare,[13] they might be confounding variables when studying the influence of socio-environmental context on discomfort from glare and have to be controlled.

### 3.2. Applicability of the Discomfort Glare Metrics

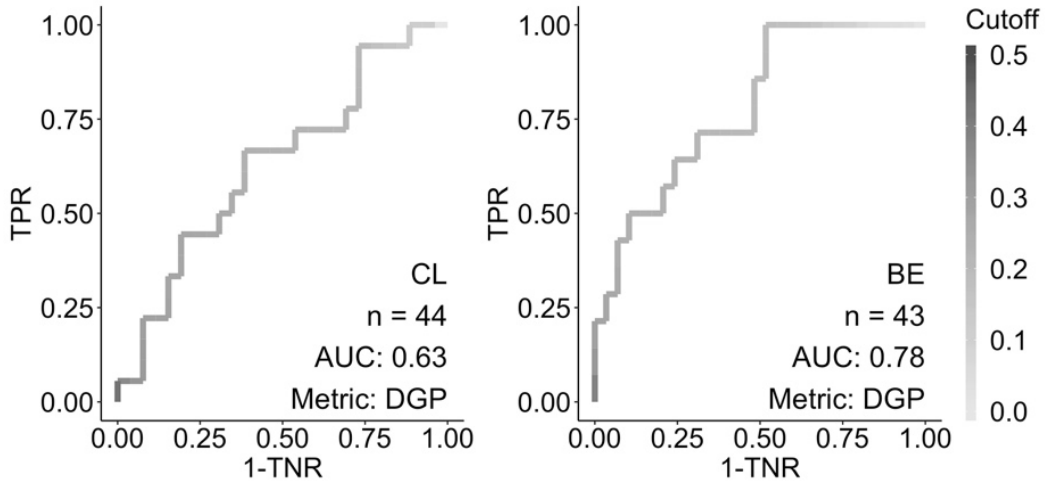
Before evaluating the differences in discomfort from glare between the four socio-environmental contexts, the effectiveness of the discomfort glare metrics in predicting discomfort from glare in each context was tested. The goal is to establish whether the five selected metrics can be used in the four contexts to predict the subjective assessments of discomfort glare. For this purpose, the relationship between the subjective assessments of discomfort glare from daylight made on the 4-point glare rating scale and the five discomfort glare metrics is analyzed through Spearman's rank correlations (Table 6).

**Table 6**: Spearman's ρ correlation coefficients between each discomfort glare metric and the subjective assessments on the 4-point glare rating scale for each socio-environmental group

| Socio-environmental | Spearman's ρ | | | | |
|---|---|---|---|---|---|
| context | DGP | DGI | CGI | $E_v$ | $L_{mean}$ |
| CL | 0.360 | 0.306 | 0.355 | 0.404 | 0.399 |
| BE | 0.392 | 0.395 | 0.366 | 0.399 | 0.377 |
| JP | 0.120 | 0.155 | 0.163 | 0.101 | 0.113 |
| CH | 0.494 | 0.527 | 0.529 | 0.434 | 0.423 |

Using Ferguson's effect size benchmarks, the correlations for the Chilean, Belgian, and Swiss contexts are observed to show a practically significant to moderate effect, whereas there seems to be no correlations between the subjective assessments and the glare metrics in Japan.

To test again the applicability of the discomfort glare models in the Japanese context, the second subjective assessment of discomfort glare from daylight, the one made through the OEQ, is used. Since this subjective assessment is in the form of a binary variable (no glare report – glare report), the Spearman's rank correlation cannot be applied. Instead, a Receiver Operating Curve (ROC) curve analysis is conducted. Only the ROC curves for the DGP are shown in Figure 7, but the Area Under the Curve (AUC) of the ROC curves for each of the five metrics are given in Table 7.



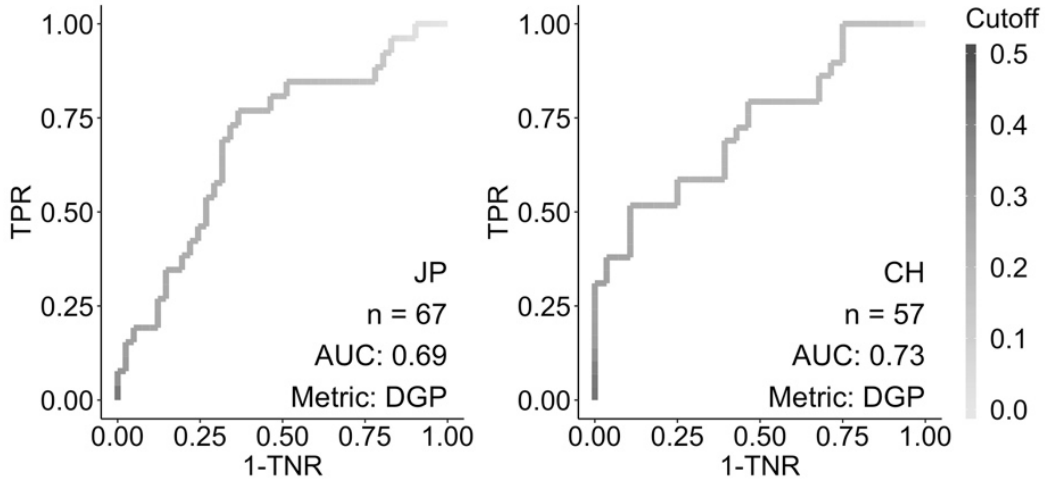



**Figure 7**: Receiver Operating Characteristic (ROC) curves from the analyses of DGP performance in predicting the binary glare report derived from the open-ended question in Chile (Fig.7a - left), Belgium (Fig.7b - center-left), Japan (Fig.7c - center right), and Switzerland (Fig.7d - right)

Figure 7 shows that the Belgian, Japanese, and Swiss ROC curves bend towards the upper left corner of the graphs, and the AUC values for these three contexts are in the range of 0.67 to 0.79 (Table 7). The DGP appears therefore as an acceptable model to discriminate between view conditions with no glare report and those with glare report for these groups.

Interestingly, the results of the ROC analysis for the Japanese group differ from the outcome of the Spearman analysis (i.e., reasonable discrimination for the ROC analysis versus no significance for the Spearman correlation). This is surprising as a recent cross-validation study[10] showed that these two statistical approaches agree on the outcome. We assume therefore that the question with the 4-point glare rating scale was not correctly understood by the participants in that socio-environmental context. This hypothesis is based on further investigations together with an additional native Japanese speaker, who was not familiar with the field of lighting. According to her, the rather technical term used for the translation of “glare” in the Japanese questionnaire was very likely not understood by Japanese people not working in the field of lighting. Even though a definition of glare was provided separately, the participants might not have taken the time to read this explanation and therefore misunderstood the question. Although this hypothesis cannot be confirmed from the collected data, this result demonstrates the importance of making an accurate translation of a questionnaire.

**Table 7**: Area Under the Curve (AUC) values derived from the Receiver Operating Characteristic (ROC) curve analyses for each of the five discomfort glare metric performances in predicting the binary glare report derived from the open-ended question for each socio-environmental group

| Socio-environmental context | AUC | | | | |
|---|---|---|---|---|---|
| | DGP | DGI | CGI | $E_v$ | $L_{mean}$ |
| CL | 0.63 | 0.60 | 0.63 | 0.63 | 0.65 |
| BE | 0.78 | 0.78 | 0.76 | 0.79 | 0.76 |
| JP | 0.69 | 0.68 | 0.71 | 0.67 | 0.67 |
| CH | 0.73 | 0.72 | 0.72 | 0.72 | 0.72 |

We can also observed in Figure 7 that the ROC curve of the Chilean group is more flat than the others, and the AUC values of this context indicate an almost failing model for DGI and poor models for the four other metrics when interpreted against the benchmarks available in the literature. From informal discussions with the participants in the Chilean context, it seems that an association between daylight and thermal discomfort in the Chilean context may exist, which could explain these results. Very often, the participant would explain that the shading devices had to stay closed to avoid thermal discomfort in the office. Because of this implicit association, some Chilean participants might have complained about daylight or the

sun in their answer to the OEQ, which was interpreted by the investigator as visual discomfort from daylight glare, whereas they meant thermal discomfort from solar heat gains. Unfortunately, this hypothesis needs further data to be confirmed.

### 3.3. Influence of the Socio-Environmental Context

In the previous sections, the five daylight discomfort glare metrics appeared to be reasonable models for predicting discomfort from glare in the four studied socio-environmental contexts. However, the robustness of the metric predictions varied depending on the subjective assessment method used in the Chilean and Japanese socio-environmental contexts. The analyses to test the influence of the socio-environmental context on discomfort from daylight glare thus have to be conducted with consideration for both subjective assessment methods.

First, the influence of the socio-environmental context on discomfort from glare is investigated through the subjective assessments made on the 4-point glare rating scale. Since the lighting conditions during the second evaluation were relatively similar between the four contexts (Fig. 6a), a Kruskal-Wallis test is applied to test whether the subjective assessments made on the 4-point scale vary based on the socio-environmental context. A Kruskal-Wallis test is chosen over a one-way independent-measure ANalysis Of VAriance (ANOVA), because the dependent variable is ordinal, i.e. the 4-point glare rating scale, and does not meet the assumption of normality.[65] Furthermore, this test is only applied to look at the difference in the subjective assessments between three socio-environmental contexts, since it seems that the 4-point glare rating scale was not correctly understood in the Japanese context. From the Kruskal-Wallis test, no statistically significant differences ($\chi2(df = 2) = 4.69$, p-value = 0.09) are found among the three socio-environmental contexts.

To take into account the lighting conditions, a second analysis looks at the difference of the metric values between the three socio-environmental contexts for each category of the 4-point scale. Since the distributions within the socio-environmental groups were not always normally distributed, Kruskal-Wallis tests are chosen over one-way independent-measure ANOVAs. Four Kruskal-Wallis tests, one for each category of the scale, are repeatedly applied for each daylight discomfort glare metric to test whether the mean ranked metric values are significantly different between the socio-environmental contexts. The dependent variables of the Kruskal-Wallis tests are therefore each of the five daylight discomfort glare metrics, and the independent variable is the socio-environmental context. The results of the Kruskal-Wallis tests, available in Table 8, show no statistically significant differences between the three socio-environmental contexts.

**Table 8**: Results of the Kruskal-Wallis tests assessing the statistical significance of the difference between the three socio-environmental contexts in the values of each of the five discomfort glare metrics for each category of the 4-point glare rating scale; a corrected significance level of 0.01 is applied

| Metric | Response category | $\chi2(df = 2)$ | p-value |
|---|---|---|---|
| DGP | No discomfort | 5.08 | 0.079 |
| | Small discomfort | 2.71 | 0.258 |
| | Moderate discomfort | 2.67 | 0.263 |
| | Large discomfort | 1.08 | 0.581 |
| DGI | No discomfort | 5.22 | 0.074 |
| | Small discomfort | 3.77 | 0.152 |
| | Moderate discomfort | 0.77 | 0.681 |
| | Large discomfort | 0.60 | 0.739 |
| CGI | No discomfort | 4.35 | 0.114 |
| | Small discomfort | 2.97 | 0.227 |
| | Moderate discomfort | 1.77 | 0.413 |
| | Large discomfort | 0.64 | 0.726 |
| $E_v$ | No discomfort | 8.63 | 0.013 |
| | Small discomfort | 3.26 | 0.195 |

| | | | |
|---|---|---|---|
| | Moderate discomfort | 2.33 | 0.313 |
| | Large discomfort | 0.64 | 0.726 |
| $L_{mean}$ | No discomfort | 8.21 | 0.016 |
| | Small discomfort | 2.39 | 0.302 |
| | Moderate discomfort | 2.58 | 0.275 |
| | Large discomfort | 1.60 | 0.449 |

To better understand these results, the distributions of the DGP values can be compared visually across the socio-environmental contexts for each category in Figure 8.

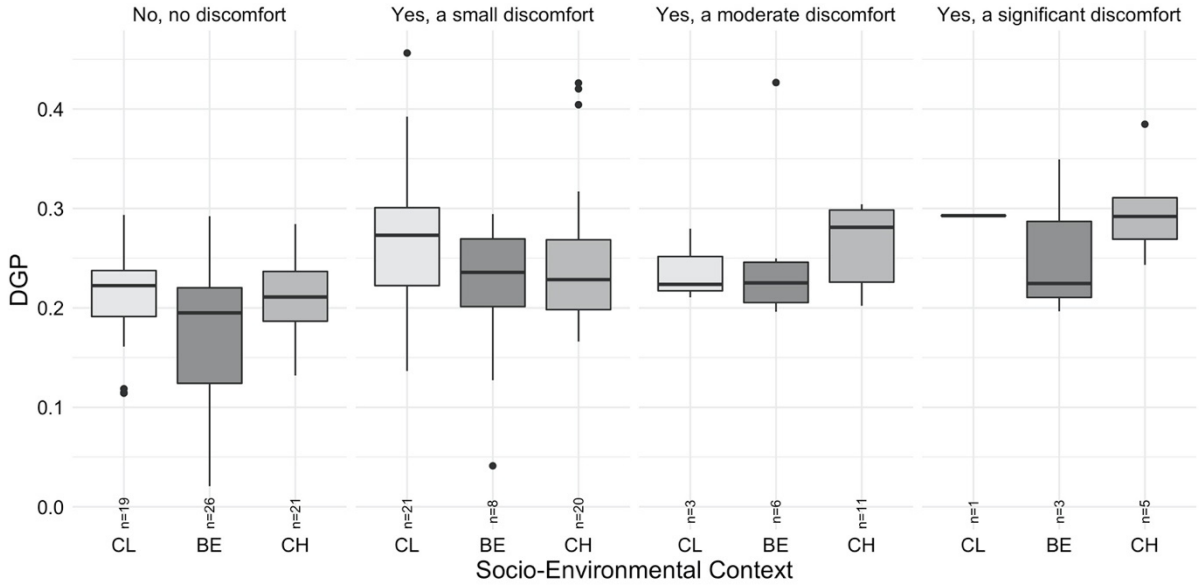



**Figure 8**: Box plots representing the distributions of the DGP values in each of the three socio-environmental contexts for each category of the 4-point glare rating scale

The two central box plots, i.e., those for the categories “Yes, a small discomfort” and “Yes, a moderate discomfort”, should be primarily considered. This is because the box plots for the categories “No, no discomfort” and “Yes, a large discomfort” depend on extreme lighting scenes and on the occurrence of those extreme scenes in each context. The box plots for these categories can therefore hardly be compared. For instance, it can be seen in Figure 6a that there were more scenes with low light levels in the Belgian context. This tendency is reflected in the box plot of the Belgian group in the “No, no discomfort” category as its 25$^{th}$ percentile is much lower than that of the two other box plots.

Furthermore, it should be noted that, in some groups, the number of data points is very low. When a group size is small ($n < 5$), the test statistic does not properly follow a $\chi 2$ distribution,[66] making the test much less reliable. The results of these Kruskal-Wallis tests should therefore be interpreted carefully.

Then, the influence of the socio-environmental context is investigated through the subjective assessments made via the OEQ. A Kruskal-Wallis test is applied to evaluate whether the rate of binary glare report from the OEQ differs between the four socio-environmental contexts. No statistically significant differences ($\chi 2(df = 3) = 3.67$, p-value= 0.30) are found among the four socio-environmental contexts.

Furthermore, since the subjective assessments derived from the OEQ are binary (0 for no glare report – 1 for glare report), multiple logistic regression models can be derived as in Equation 2. No interaction term is used in the models due to the results of an LRT depicting that the data was not more likely under a model with an interaction term than under a model without it.

$$subj.\ assessment\ [0|1] \sim glare\ metric \left\{ \begin{matrix} DGP \\ CGI \\ DGI \\ E_v \\ L_{mean} \end{matrix} \right\} + socio\ env.c\ ontext\ [CL|BE|JP|CH] \quad \text{Eq.2}$$

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 through Wald tests (Table 9) and LRT (Table 10). 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 9.

**Table 9**: Results of the Wald tests assessing the statistical significance of the independent variables, i.e. the five discomfort glare metrics and the binary transformations of the socio-environmental context, of each multiple logistic regression model in predicting the binary glare report derived from the open-ended question; a corrected significance level of 0.01 is applied

| Model using… | Independent variable tested | Estimated parameter | χ2(df = 1) | p-value |
|---|---|---|---|---|
| DGP | DGP | 12.65 | 4.60 | 0.000*** |
| | CH/BE | -0.36 | -0.79 | 0.429 |
| | CH/JP | -0.26 | -0.66 | 0.512 |
| | CH/CL | -0.46 | -1.07 | 0.285 |
| DGI | DGI | 0.14 | 4.45 | 0.000*** |
| | CH/BE | -0.70 | -1.57 | 0.117 |
| | CH/JP | -0.61 | -1.57 | 0.117 |
| | CH/CL | -0.75 | -1.72 | 0.086 |
| CGI | CGI | 0.13 | 4.81 | 0.000*** |
| | CH/BE | -0.55 | -1.19 | 0.233 |
| | CH/JP | -0.50 | -1.29 | 0.197 |
| | CH/CL | -0.64 | -1.45 | 0.147 |
| $E_v$ | $E_v$ | 0.00 | 4.28 | 0.000*** |
| | CH/BE | -0.42 | -0.94 | 0.346 |
| | CH/JP | -0.37 | -0.96 | 0.339 |
| | CH/CL | -0.46 | -1.06 | 0.289 |
| $L_{mean}$ | $L_{mean}$ | 0.00 | 4.24 | 0.000*** |
| | CH/BE | -0.41 | -0.90 | 0.369 |
| | CH/JP | -0.28 | -0.73 | 0.467 |
| | CH/CL | -0.30 | -0.69 | 0.492 |

**Table 10**: Results of the Likelihood Ratio Test (LRT) assessing the statistical significance of the socio-environmental context variable of each multiple logistic regression model in predicting the binary glare report derived from the open-ended question; a corrected significance level of 0.01 is applied

| Model using… | Independent variable tested | χ2(df = 3) | p-value |
|---|---|---|---|
| DGP | Socio-environmental context | 1.31 | 0.726 |
| DGI | Socio-environmental context | 4.19 | 0.242 |
| CGI | Socio-environmental context | 2.78 | 0.427 |
| $E_v$ | Socio-environmental context | 1.57 | 0.667 |
| $L_{mean}$ | Socio-environmental context | 0.99 | 0.805 |

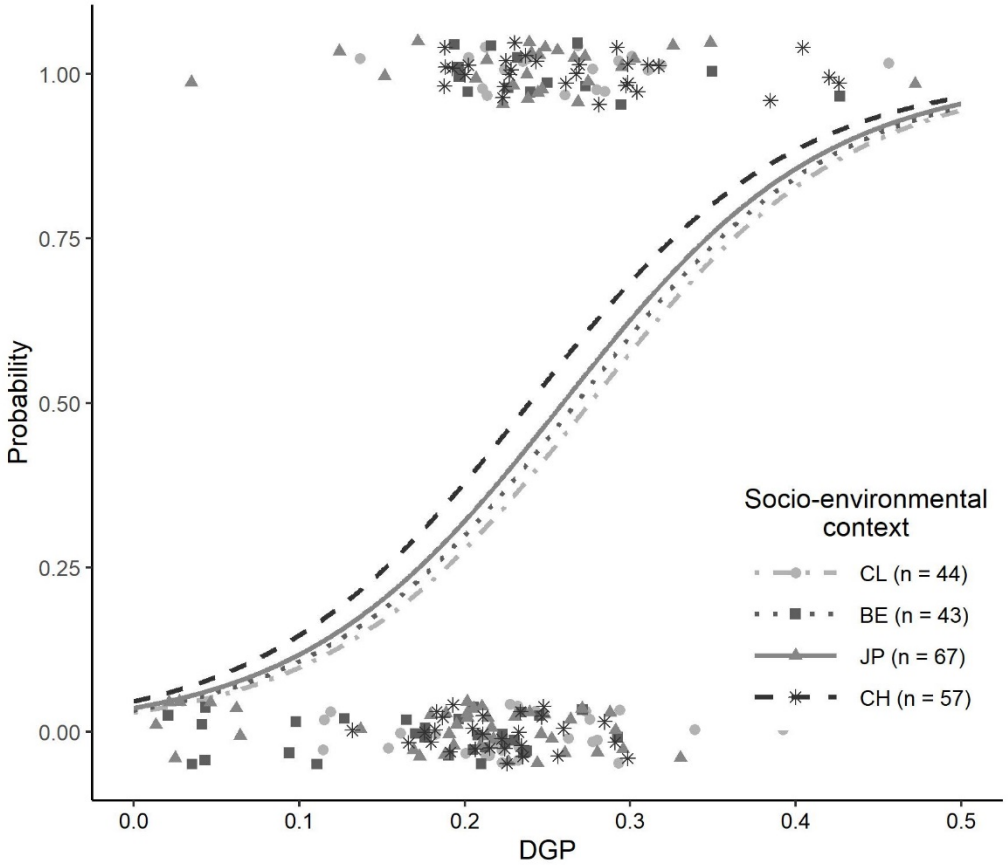



**Figure 9**: Logistic growth curve of the multiple logistic regression model using the DGP and the socio-environmental context to predict the binary glare report derived from the open-ended question; the dots represent the real subjective assessments made by the participants (0 for no glare report – 1 for glare report); some jitter has been added to the graph for visibility

The results of the tests applied indicate no statistically significant influence of the socio-environmental context on discomfort from daylight glare. The five daylight discomfort glare metrics, however, are found to be statistically significant variables of the multiple logistic regression models (Table 9), implying that the metrics can be used to predict the subjective assessments of discomfort glare in these contexts.

In Figure 9, the logistic growth curves of the four socio-environmental contexts are close to each other, but a slight shift in between the different contexts can still be observed. These shifts seem to be, however, not statistically significant according to either the Wald tests or LRT and might be due to some noise or experimental bias in the data.

Furthermore, these statistical analyses were repeated to test whether the language of the questionnaire (i.e. Spanish, French, Japanese, or English) could have been a confounding variable. Since a large part of the Swiss participants answered the French questionnaire, the influence of the socio-environmental context on discomfort from glare was checked again while considering only the French-speaking Belgian participants and the French-speaking Swiss participants. The results of the analyses were similar to those described above and are available in the Supplementary Materials 4.

At last, to check that there is no confounding effect with the participants' iris pigmentation, chronotype, or attractiveness of the view through the window, the influence of the socio-environmental context on discomfort from glare is tested a second time through multiple logistic regression models including these three potentially confounding variables. In this way, the potential confounding effect of these variables is controlled. Both Wald tests and LRT were applied on the modified models, and both showed no statistically significant influence of the socio-environmental context, as can be seen in Table 11 for LRT.

**Table 11**: Results of the Likelihood Ratio Test (LRT) assessing the statistical significance of the socio-environmental context variable for each multiple logistic regression model in predicting the binary glare report derived from the Open-Ended Question (OEQ) while controlling for a potential confounding effect of the iris pigmentation, chronotype, or attractiveness of the view through the window; a corrected significance level of 0.01 is applied

| Model using… | Independent variable tested | $\chi 2(df = 3)$ | p-value |
|---|---|---|---|
| DGP | Socio-environmental context | 0.78 | 0.855 |
| DGI | Socio-environmental context | 3.33 | 0.343 |
| CGI | Socio-environmental context | 2.28 | 0.517 |
| $E_v$ | Socio-environmental context | 0.92 | 0.822 |
| $L_{mean}$ | Socio-environmental context | 0.91 | 0.822 |

Based on all test results conducted to investigate the influence of the socio-environmental context on discomfort from glare (i.e. Kruskal-Wallis tests, Wald tests and LRT), no evidence of a statistically significant difference in participants' discomfort from daylight glare between the different socio-environmental contexts was found. This is true for both subjective assessment methods and the five daylight discomfort glare metrics applied. This study therefore does not support the hypothesis that discomfort from daylight glare differs between people from different socio-environmental contexts.

## 4 Discussion

The difference in discomfort from glare between various socio-environmental contexts, which has been either observed or suggested in the literature,[17,19,21,22,24,26,27,38] might be due to differences in the protocol between the studies used in the comparison, as first suggested by Iwata et al.[21] In the literature, there are eight studies in which the hypothesis that people from different socio-environmental contexts have different tolerances towards discomfort glare is supported. In seven[17,19,21,22,24,26,38] of these eight studies, this hypothesis is deduced based on the comparison of evaluations of discomfort glare with the evaluations of a formerly published study. At the very least, the investigator(s) and equipment are not the same between the two studies of comparison; at worst, the entire protocol differs between the two studies. A more detailed analysis of the differences between the protocol of each study would be useful to have a better understanding of which element(s) might have caused the differences in discomfort from glare. In the last study supporting the hypothesis,[27] the comparison between the sensitivity to discomfort glare of two different socio-environmental 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 8 Caucasians.

In comparison, the data used in this study constitutes four balanced socio-environmental groups, each of which is composed of at least 40 participants, and was collected with the same investigator, equipment, and protocol. This data did not lead to evidence supporting the findings of previous studies that suggested a difference in discomfort from glare 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 from daylight glare between Middle-Eastern and Japanese participants,[28] although it is not said for how long the Middle-Eastern participants had been living in the Japanese socio-environmental context and whether they had acclimatized to it. Secondly, from another laboratory study using virtual reality, no differences in subjective visual perception of architectural spaces could be detected between 138 participants in the Greek socio-environmental context and 120 participants in the Swiss context.[36]

## 5 Limitations

The non-statistical significance of the socio-environmental context as a variable influencing discomfort from glare might be related to some limitations of this study, as listed below:

- The data for the Chilean socio-environmental context was collected in three cities with different latitudes, and therefore different climates and daylight conditions. The Chilean socio-environmental context might have been mitigated by the merging of these three different cities.
- It was observed that three additional factors, namely the iris pigmentation, chronotype, and view through the window, were not distributed in a similar way for the four socio-environmental groups. Although the literature is inconclusive on the influence of these factors on discomfort from glare and the statistical analyses seem to show no confounding effects with the socio-environmental context, they still might be confounding variables and should be further studied in the future.
- The minimum sample size in this study was evaluated based on the assumption that there is a difference of 40% between reports of discomfort glare in real offices in the Western context and in the Asian context, as shown in the literature. In this study, the percentage of glare report in usual working conditions was of 27% in Japan, 30% in Belgium and Switzerland, and 34% in Chile. Based on these last probabilities, the minimum sample size would have been evaluated at 680 glare evaluations for each socio-environmental context.
- None of the four studied socio-environmental contexts endure an extreme variation in daylight hours throughout the year. In socio-environmental contexts with more extreme variation, this result should be interpreted carefully as it was reported that shortage of sunlight could create a general positive attitude to it that may influence discomfort from glare.[67]
- The time allocated to adapt to the lighting conditions in which daylight is maximized (around 5 min) might be seen as relatively limited. However, the exact time required for a subject's eyes to adapt to a new view condition is still unknown.
- Modifying the lighting conditions between the two glare evaluations without randomization (the more discomforting scene was always the second one, when the lighting conditions had been changed) most probably biased the subjective assessments of discomfort glare. Furthermore, participants' attention might have been drawn onto their visual discomfort, which may have also biased their subjective assessments. At last, the imbalance in the 4-point scale with three discomfort labels out of four might also have induced bias into participants' subjective assessment. However, these potential biases were the same in each socio-environmental context and should therefore not have hindered the comparison. It would anyway be useful to repeat this study in real office buildings where discomfort glare from daylight occurs naturally, and with reduced biases related to reports of discomfort glare.
- The view conditions investigated during the field study were carefully selected to maximize the occurrence of saturation glare from daylight. The findings of this study might therefore be different under contrast glare from daylight, although daylight is more often associated with saturation glare.

## 6 Conclusion

In this study, the influence of the socio-environmental context on discomfort from daylight glare was investigated. For this purpose, 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. 211 data points consisting of a subjective assessment of discomfort glare and 5 daylight discomfort glare metrics were analysed. The subjective assessment of discomfort glare consisted of an evaluation made by the participant on a 4-point glare rating scale, as well as a binary glare report derived from the participants' answers to an OEQ. The five daylight discomfort glare metrics, namely the DGP, CGI, DGI, $E_v$, and $L_{mean}$, were selected in order to be the best performing and most robust of their type. The hypothesis that was tested in this study predicted that people from at least one of the four

socio-environmental contexts have a different sensitivity to discomfort glare from daylight than people from another one of the four contexts.

First of all, the results suggest that the five daylight discomfort glare metrics are acceptable models to discriminate between view conditions that were reported as discomforting and not discomforting by the participants of the four contexts. This already demonstrates a certain universality of the metrics.

Furthermore, some observations led to the hypothesis that the subjective assessments made via the glare rating scale in the Japanese context were biased due to translation issue. The question of defining a universal method to collect the least biased subjective assessments of discomfort glare is fundamental to produce relevant knowledge in the field of discomfort glare. In the future, it is highly recommended that dedicated studies try to address it.

At last, the analyses of the data collected could not demonstrate any statistically significant differences in discomfort from daylight glare between the participants from the four socio-environmental contexts. This result was further supported by additional analyses conducted on the data including the non-acclimatized participants. Such result was not expected in view of the existing literature on the topic. Further research, not restricted by the limitations of this study, is therefore required to reproduce this finding.

Upon validation by further studies, this outcome would imply that there would be no acclimatization process influencing discomfort from daylight glare. Consequently, the results of discomfort glare research conducted around the world could be globalized and compared without the risk of bias related to the socio-environmental context of the population tested. Furthermore, research efforts could focus on improving one general approach to predict discomfort from daylight glare perception from daylight, rather than each region developing its own discomfort glare metric.

**Funding**

Clotilde Pierson is a Research Fellow of the Fonds de la Recherche Scientifique – FNRS. The study in Japan was supported by JSPS KAKENHI Grant Number JP 18H01599.

**Acknowledgements**

The authors would like to thank Laura Marín Restrepo, Kineya Morales, Margarita Cordaro Cárdenas, Joel Becerra Fuentes, Hernán Madrid, Jorge Cortes Pereira, Adrian Melian Vivar, Hatsumi Hagiwara, Prof. Etsuko Mochizuki, Saad Al-Kuwari, Ryohei Takagi, Chunqi Zhu, and all the persons who helped to conduct the study in Chile, Belgium, Japan, and Switzerland.

**Declaration of Conflicting Interests**

No potential conflict of interest was reported by the authors.

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**References**

1. Heschong L, Wright RL, Okura S. Daylighting Impacts on Human Performance in School. LEUKOS 2002; 31: 101–114.
2. Heschong L, Wright RL, Okura S. Daylighting Impacts on Retail Sales Performance. LEUKOS 2002; 31: 21–25.
3. Boyce P, Hunter C, Howlett O. The Benefits of Daylight through Windows. New York, USA: Lighting Research Center - Rensselaer Polytechnic Institute, 2003.
4. Boubekri M. Daylighting, Architecture and Health - Building Design Strategies. Oxford, UK: Elsevier, 2008.

5. Rockcastle SF, Andersen M. Celebrating contrast and daylight variability in contemporary architectural design: a typological approach. In: Lux Europa 2013. Krakow, Poland, 2013.
6. Athienitis AK, Tzempelikos A. A methodology for simulation of daylight room illuminance distribution and light dimming for a room with a controlled shading device. Solar Energy 2002; 72: 271–281.
7. Franzetti C, Fraisse G, Achard G. Influence of the coupling between daylight and artificial lighting on thermal loads in office buildings. Energy and Buildings 2004; 36: 117–126.
8. Sabry H, Sherif A, Gadelhak M, Aly M. Balancing the daylighting and energy performance of solar screens in residential desert buildings: examination of screen axial rotation and opening aspect ratio. Solar Energy 2014; 103: 364–377.
9. CIE. Technical Report: Discomfort Glare in the Interior Working Environment. N° 55:1983, Vienna, Austria: Commission Internationale de l'Eclairage, 1983.
10. Wienold J, Iwata T, Sarey Khanie M, Erell E, Kraftan E, Rodriguez R, Yamin Garreton JA, Tzempelikos T, Konstantzos I, Christoffersen J, Kuhn TE, Pierson C, Andersen M. Cross-validation and robustness of daylight glare metrics. Lighting Research & Technology 2019; 51(7): 983–1013. DOI: 10.1177/1477153519826003.
11. Kent MG. Temporal Effects in Glare Response. PhD Thesis. University of Nottingham (UK), 2016.
12. Pierson C. Discomfort Glare Perception from Daylight: Influence of the Socio-Environmental Context. PhD Thesis. Université catholique de Louvain (Belgium), 2019.
13. Pierson C, Wienold J, Bodart M. Review of factors influencing discomfort glare perception from daylight. LEUKOS 2018; 14: 111–148.
14. Lysgaard S. Adjustment in a foreign society: norwegian Fulbright grantees visiting the United States. International Social Science Bulletin 1955; 7: 45–51.
15. Black JS, Mendenhall M. The U-Curve adjustment hypothesis revisited: a review and theoretical framework. Journal of International Business Studies 1991; 22: 225–247.
16. Luckiesh M, Guth SK. Brightnesses in Visual Field at Borderline Between Comfort and Discomfort (BCD). In: National Technical Conference of the Illuminating Engineering Society. French Lick, USA, 1949.
17. Ichikawa H, Chonan T. Fundamental study on brightness in visual field at borderline between comfort and discomfort (BCD). Journal of the Illuminating Engineering Institute of Japan 1964; 48: 476–481.
18. MacGowan D, Aspinall P, Newman P, Russell T, Lakowski R. Visual Quality Characteristics of the Working Environment. Glasgow, UK: Inter-Institutional Research Programme, 1988.
19. Subova A, Kittler R, MacGowan D. Results of ongoing experiments on subjective response to discomfort glare. Journal of the illuminating Engineering Institute of Japan 1991; 75: 129–130.
20. Petherbridge P, Hopkinson RG. Discomfort glare and the lighting of buildings. Lighting Research & Technology 1950; 15: 39–79.
21. Iwata T, Shukuya M, Somekawa N, Kimura KL. Experimental study on discomfort glare caused by windows: subjective response to glare from a simulated window. Journal of Architecture, Planning and Environmental Engineering 1992; 432: 21–33.
22. Pulpitlova J, Detkova P. 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, 1993.
23. Tokura M, Iwata T, Shukuya M. 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 1996; 489: 17–25.
24. Iwata T, Velds M, Van der Voorden M. Effect of eye color on response to discomfort glare caused by a large source. In: ICHES 1998. Yokohama, Japan, 1998.
25. Hopkinson RG. Glare from windows - using the glare index in daylighting design. Construction Research Development 1971; 3: 23–28.

26. Lee JS, Kim BS. Development of the nomo-graph for evaluation on discomfort glare of windows. Solar Energy 2006; 81: 799–808.
27. Ko JK, Choi SY. Contents development for office smart lights. In: CIE 2017: smarter lighting for better life. Jeju, South Korea, 2017.
28. Iwata T. Difference in Evaluation of Discomfort Glare from Windows between Middle-Eastern and Japanese Students. In: EuroSun 2018. Rapperswil, Switzerland, 2018.
29. Hirashima SQ, Katzschner A, Ferreira DG, Sad de Assis E, Katzchner L. Thermal comfort comparison and evaluation in different climates. Urban Climate 2018; 23: 219–230.
30. Kenawy I, Elkadi H. The impact of cultural and climatic background on thermal sensation votes. In: PLEA2013. Munich, Germany, 2013.
31. Aljawabra F, Nikolopoulou M. Thermal comfort in urban spaces: a cross-cultural study in the hot arid climate. International Journal of Biometeorology 2018; 62: 1901–1909.
32. Knez I, Thorsson S. Influences of culture and environmental attitude on thermal, emotional and perceptual evaluations of a public square. International Journal of Biometeorology 2006; 50: 258–268.
33. Belcher M. Cultural aspects of illuminance levels. Lighting Design and Application 1985; 15: 49–50.
34. Park N-K, Pae JY, Meneely J. Cultural preferences in hotel guestroom lighting design. Journal of Interior Design 2010; 36: 21–34.
35. Kim DH, Mansfield KP. A cross-cultural study on perceived lighting quality and occupants' well-being between UK and South Korea. Energy and Buildings 2016; 119: 211–217.
36. Chamilothori K. Perceptual effects of daylight patterns in architecture. PhD Thesis. Ecole Polytechnique Fédérale de Lausanne (Switzerland), 2019. DOI: 10.5075/epfl-thesis-9553.
37. Konis K. 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 2014; 77: 67–79.
38. Mangkuto RA, Kurnia KA, Azizah DN, Atmodipoero RT, Soelami FXN. Determination of discomfort glare criteria for daylit space in Indonesia. Solar Energy 2017; 149: 151–163.
39. Craig T, Conniff A, Galan-Diaz C. The Influences of Actual and Perceived Familiarity on Environmental Preferences for the Design of a Proposed Urban Square. Urban Studies Research 2012; 2012: e767049.
40. Lee H-W. Perceptive of expatriation and cross-cultural adjustment. The Journal of Global Business Management 2006; 2(1).
41. Ward CA, Bochner S, Furnham A. The Psychology of Culture Shock. Hove, UK: Routledge - Taylor & Francis Group, 2001.
42. Faul F, Erdfelder E, Buchner A, Lang AG. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. Behavior Research Methods 2009; 41: 1149–1160.
43. Green SB. How many subjects does it take to do a regression analysis ? Multivariate Behavioral Research 1991; 26: 499–510.
44. Uttley J. Power analysis, sample size, and assessment of statistical assumptions—improving the evidential value of lighting research. LEUKOS 2019; 15: 143-162. DOI: 10.1080/15502724.2018.1533851.
45. Bach M. The Freiburg Visual Acuity test - Automatic measurement of visual acuity. Optometry & Vision Science 1996; 73: 49–53.
46. Tuaycharoen N, Tregenza PR. View and discomfort glare from windows. Lighting Research & Technology 2007; 39: 185–200.
47. Wienold J, Christoffersen J. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Buildings 2006; 38: 743–757.
48. Hirning M, Isoardi G, Coyne S, Cowling I. Applying the Use of High Dynamic Range Imaging Pipelines to Discomfort Glare Research. In: CIE 2010: lighting quality & energy efficiency. Vienna, Austria, 2010.

49. Pierson C, Cauwerts C, Bodart M, Wienold J. Tutorial: Luminance Maps for Daylighting Studies from High Dynamic Range Photography. LEUKOS 2020. DOI: 10.1080/15502724.2019.1684319.
50. Pierson C, Wienold J, Bodart M. Daylight discomfort glare evaluation with evalglare: influence of parameters and methods on the accuracy of discomfort glare prediction. Buildings 2018; 8(8): 94.
51. Field A, Miles J, Field Z. Discovering Statistics Using R. London, UK: SAGE Publications Ltd, 2012.
52. Rice WR. Analyzing tables of statistical tests. Evolution 1989; 43: 223.
53. Cabin RJ, Mitchell RJ. To Bonferroni or not to Bonferroni: when and how are the questions. Bulletin of the Ecological Society of America 2000; 81: 246–248.
54. Ferguson CJ. An effect size primer: a guide for clinicians and researchers. Professional Psychology: Research and Practice 2009; 40: 532–538.
55. Hosmer DW, Lemeshow S, Sturdivant RX. Applied Logistic Regression - Second Edition. Hoboken, USA: John Wiley & Sons, 2013.
56. 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.
57. Mutz D, Pemantle R. The Perils of Randomization Checks in the Analysis of Experiments. University of Pennsylvania, 2012.
58. Vanhove J. Silly significance tests: Balance tests. https://janhove.github.io/reporting/2014/09/26/balance-tests (accessed on 04/12/2019)
59. Hayes RJ, Moulton LH. Cluster Randomised Trials - Second Edition. Boca Raton: CRC Press, 2017.
60. Katsara M-A, Nothnagel M. True colors: A literature review on the spatial distribution of eye and hair pigmentation. Forensic Science International: Genetics 2019; 39: 109–118.
61. Hohl DM, Bezus B, Ratowiecki J, Catanesi CI. Genetic and phenotypic variability of iris color in Buenos Aires population. Genetics and Molecular Biology 2018; 41: 50–58.
62. Leocadio-Miguel MA, Louzada FM, Duarte LL, Areas RP, Alam M, Freire MV, Fontenele-Araujo J, Menna-Barreto L, Pedrazzoli M. Latitudinal cline of chronotype. Scientific Reports 2017; 7: 5437. DOI: 10.1038/s41598-017-05797-w.
63. Randler C. Morningness-eveningness comparison in adolescents from different countries around the world. Chronobiology International 2008; 25: 1017–1028.
64. Randler C, Prokop P, Sahu S, Haldar P. Cross-cultural comparison of seven morningness and sleep-wake measures from Germany, India and Slovakia. International Journal of Psychology 2014; 50: 279–287.
65. Field A, Hole GJ. How to Design and Report Experiments. SAGE Publications Inc, 2002.
66. McDonald JH. Handbook of Biological Statistics. Baltimore, USA: Sparky House, 2014.
67. Matusiak BS. Glare from a translucent facade, evaluation with an experimental method. Solar Energy 2013; 97: 230–237.

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