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Daylighting Through Electrochromic Glazing Under Overcast Skies: Impacts on Visual Task Performance and Perception

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ABSTRACT
Electrochromic (EC) glazing allows modulating the intensity of visual and solar transmission by dynamically switching between bleached (clear) and tinted (colored) states, leading to changes in spectral power distribution (SPD), correlated color temperature (CCT), and illuminance of the incoming daylight. In this experimental study, we investigated the impact of spectral composition of daylight filtered through a 6-pane EC façade on visual task performance and visual perception. In a semi-controlled test room, 19 subjects were exposed to five setting scenarios of the EC façade (fully bleached, mixed setting after fully bleached, fully tinted, mixed setting after fully tinted, and user-controlled). Test subjects performed a series of visual tasks, and their assessments of the indoor environment and of the outside view were collected along with luminous and spectral measurements under each condition. The analysis provided statistical evidence that the changes in spectral composition of daylight do not have a practically relevant effect on visual task performance in terms of visual acuity and color naming accuracy. However, the daylight filtered through the fully tinted glazing had a substantive impact on visual perception, evoking negative responses to the color rendering of the indoor environment and of the outside view. A mixed settings of the EC façade could improve a natural assessment of the incoming light compared to the fully tinted state, achieving better ratings in terms of perception of the indoor and outdoor environments. When given control of the EC glazing, subjects expressed higher acceptance and satisfaction compared to the tinted and mixed scenarios.

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1. Introduction

Advanced daylighting and shading systems can enhance the luminous quality and energy performance of buildings. Among these, electrochromic (EC) glazing dynamically modulates the intensity of visual and solar transmission by switching between bleached (clear) and tinted (colored) states (Rubin et al. 1994). Compared to windows equipped with conventional double-glazed units (DGU), EC glazing has the potential to reduce extreme variations in illuminance, protect against undesired light ingress, provide modulation of luminance ratios (Lampert 1998; Moeck et al. 1996), and potentially enhance energy savings (Ciampi et al. 2020; Scorpio et al. 2020), while preserving unobstructed views to the outdoors (Piccolo and Simone 2009).

To support advances in EC glazing technology and their controlling logics, recent research has particularly focused on user acceptance and satisfaction (Day et al. 2019; Mardaljevic et al. 2016). Although the EC glazing can reduce excessive illumination, the risk of discomfort glare from low angle direct sun or high sky luminance has, at times, been reported by occupants, which would entail switching the EC glazing to very low transmittance states (Clear et al. 2006; Jain et al. 2021; Lee and Dibartolomeo 2002). Lowering the visible transmittance of the EC glazing, however, could reduce the availability of natural daylight with negative consequences on the quality of the visual environment (Piccolo and Simone 2009) and on lighting energy demands. In fact, earlier studies had detected a direct correlation between the operation of electrochromic glazing and increased lighting energy use (Clear et al. 2006; Lee and Dibartolomeo 2002; Moeck et al. 1996).

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To address the potentially conflicting requirements of luminous protection, control of solar gains, and access to clear views, the definition of the adequate visible transmittance range for the EC glazing is, therefore, essential. This is particularly challenging for orientations, latitudes, or times of the year that are characterized by low sun angles, which might require the integration of additional shading devices (Ajaji and André 2015; Lee and Dibartolomeo 2002; Piccolo and Simone 2009). In this context, a recent study (Jain et al. 2021) demonstrated that a visible transmittance (τv) lower than 0.6% of the EC glazing can be adequate to control discomfort glare, although the required level of protection from glare might be difficult to achieve when the sun is in the central field of view. The study also indicated that, even at such low level of τv, most participants would prefer to add an additional shading device. This, of course, might come to the detriment of an acceptable view clarity (Jain et al. 2021; Ko et al. 2022; Moeck et al. 1996). In fact, as the EC glazing tint changes, the color appearance of external elements takes on a progressively deeper blue hue, which might present potential user acceptance issues (Mardaljevic et al. 2016). Previous user subject studies reported negative ratings for the outside view from EC glazing due to perceived gloominess, a persistent sense of an overcast sky (Day et al. 2019), altered color perception of indoor and outside elements, and reduced view clarity (Jain et al. 2021).

User acceptance, feeling of brightness, and color rendering are issues of primary concern in indoor (day)lighting. These priorities have been linked to the changes in spectral power distribution (SPD) and to the light and color modulation associated with the states of the EC glazing (Arsenault et al. 2012; Jain et al. 2021; Mardaljevic et al. 2014; Piccolo and Simone 2009). It has been hypothesized that changes in the correlated color temperature (CCT) of a light source might influence the subjective evaluation of discomfort glare (Pierson et al. 2018). Some studies, in fact, detected a higher occurrence of discomfort glare with light sources characterized by shorter wavelengths (Flannagan et al. 1989; Jain et al. 2023; Yang et al. 2018). CCT modulations of electric lighting (e.g., from warm to cold or vice versa) have also been found to potentially affect user comfort, satisfaction, and alertness (Kompier et al. 2020, 2021). This could impact concentration and visual task performance (De Kort 2019; Kompier et al. 2021; Smolders et al. 2012). Liang et al. (2019) showed that an artificial window (lit using an array of LEDs, light emitting diodes) with a blue-tinted film was perceived as more unnatural, less comfortable, and less acceptable than a window with a clear glazing. In their study, subjects also incurred in more errors while performing a chromatic task compared to an achromatic task under the artificial blue window compared to a bronze and clear glazing (Liang et al. 2019). This is consistent with the findings of Kompier et al. (2020), suggesting that dynamic light with varied color temperature and illuminance may impact visual performance.

As occupants may prefer a neutral rather than tinted color of daylight (Wilkins et al. 2022), user acceptance of the visual environment produced by the EC glazing becomes one of the key determinants for the success of this technology (Lee et al. 2012). The variations in the spectrum of transmitted daylight from an EC façade, in fact, may impact the appreciation of the quality of indoor and outdoor scenes in terms of perceived color and brightness of surfaces and objects (Jain et al. 2021; Mardaljevic et al. 2016; Piccolo et al. 2009). On these bases, various studies have suggested that a combination of bleached and fully tinted EC panels might allow to achieve the required level of daylight control, whilst maintaining the potential for neutral color rendition (Jain et al. 2021, 2022; Lee et al. 2012). The perceived color of inside objects rendered through a mixture of bleached and tinted states of six EC panes was found to be perceived by occupants as mostly natural. However, the colors of the outdoor environment were still perceived as non-natural by the majority of test participants (Jain et al. 2021). In another study, a theoretical model was proposed to offer spatially homogeneous spectral transmission via combining spectral curves of bleached and tinted EC glazing (Mardaljevic et al. 2016). Nevertheless, the study pointed that, although the received daylighting spectrum might be neutral, occupant acceptance of the color appearance of windows remains mostly unknown.

As there is a continuous range in the visible transmittance of the EC glazing between bleached and tinted states, resulting in dynamic modulations of spectral power distribution (SPD), CCT and illuminance, the literature leads to postulate that the changing tint of an EC façade could have an influence on visual task performance, and on users' visual perception of the indoor and outdoor environment. This, however, needs more thorough investigation since visual response, satisfaction, and acceptance might differ based on the characteristics of daylight, its dynamic transitions, the color alteration and/or distortion of internal objects and the view toward the outside, and the management strategy that is applied to the EC glazing (particularly if occupants are left with some level of control or manual override), while excluding the potential biases or confounding factors that might appear due to sudden changes in light characteristics or the occurrence of discomfort from the direct sun.

To contribute to address these questions, this study is based on the research hypothesis that the dynamic changes in spectral power distribution, color temperature, and illuminance of the incoming daylight due to the diverse settings of an EC façade would imply a change in users' visual task performance, their perception of the indoor environment, and their appreciation of the outside view.

2. Materials and methods

2.1. Experimental design

An experimental study was designed to investigate the potential subjective effects of dynamic daylight through an EC façade on visual perception and task performance in a semi-controlled environment. The study followed a *within-subject* design (repeated measurements), where every participant experienced different visual scenarios using a multi-measure approach. The minimum sample size required for the study was determined via preliminary G-power analyses (*within-factors* ANOVA test) for repeated measurements' experimental design, considering one sample group and five conditions (scenarios), and assuming an effect size of 0.30 and a power of 0.95.

Nineteen participants were recruited via an online advertisement addressed to the staff and students of the Louvain research institute for Landscape, Architecture, Built environment (LAB) at the University of Louvain (Belgium). The requirements for recruiting the participants were to have normal or corrected-to-normal eye vision, regular color perception, and being above 18 years of age. Any volunteer who did not fulfill these requirements was excluded from the sample. The participants varied in nationality and cultural background, their mean age was 31 years old ($SD = 7.95$). The sampling method, experimental design, and test procedures were approved by the IPSY ethical committee at the University of Louvain (approval number 2022-30). Participants were given a gift token (a mug with the LAB logo) as appreciation for their voluntary participation. The experiment was conducted in a test room equipped with a west-facing EC façade at the AGC Technovation Center in Gosselies, Belgium, with an office-like setup (Fig. 1).

The test room had dimensions of 3 m × 4.6 m, a height of 2.6 m, and faced due west (WWR 87%). The façade was composed of two horizontal rows of three panes of EC glazing (six panes in total). Each EC pane had a variable visible transmittance ranging from τv 65% to 2%, and a solar factor g-value ranging from 44% to 5%. Switching between extreme states, from fully bleached to fully tinted, took up to 3 min.

The experimental sessions were conducted during the months of February and March on predominantly overcast sky days. These conditions were chosen to reduce the risk of substantial and sudden changes in illuminance and daylight CCT (Condit and Grum 1964), and to minimize the potential occurrence of glare from direct sun (Jain et al. 2022), particularly in the afternoon hours. This also helped minimize potential experimental bias associated with the timing of test sessions. Days with clear skies and sunlight posed a risk of creating noticeably different conditions between morning and afternoon tests, which the overcast conditions helped mitigate. This was also reinforced by the fact that similar test conditions, e.g., when the sun is not in the FOV, low contrast scenarios, or bright diffuse

Fig. 1. The test room: external view (left); internal office-like setup (right).

skylight conditions have seldom been studied in scientific literature. The sessions were evenly distributed along the entire day, since previous studies had suggested no significant differences in activation effects of high CCT exposure on visual perception and task performance between the morning and afternoon hours (Górnicka 2008; Smolders and De Kort 2017). Daylight was the only luminous source utilized throughout the experimental procedure (with the exception of the PC screen where tasks were presented). During each session, subjects were asked to perform a series of visual tasks and to respond to a questionnaire under the various daylight conditions resulting from different tint settings of the EC panes. Subjects' responses were collected to assess:

- Visual acuity and color naming accuracy
- Sufficiency of daylight levels.
- Acceptance and satisfaction with the apparent color of internal objects.
- Acceptance and satisfaction with the external view through the EC façade.
- Acceptance of window appearance under various EC glazing settings.
- Preferences of the tint of the EC façade.

The experimental procedure was designed to study the potential activation effects on user perception and performance due to dynamic daylight transitions from warm to cold CCT, and vice versa (Kompier et al. 2021). The tint degree of the EC façade was changed from fully bleached to fully tinted, and vice-versa, through two middle states (half of the panes bleached and half of the panes tinted), while a fifth scenario left the control of the tint degree of the façade to the participant. Specifically, the five scenarios were:

- Scenario 1 (SC1): Fully bleached state (façade $\tau v = 65\%$).
- Scenario 2 (SC2): Mixed state (three top panes fully tinted and three bottom panes fully bleached (façade $\tau v = 33.5\%$)*).
- Scenario 3 (SC3): Mixed state (three top panes fully tinted and three bottom panes fully bleached (façade $\tau v = 33.5\%$)*"
- Scenario 4 (SC4): Fully tinted state (façade $\tau v = 2\%$).
- Scenario 5 (SC5): Participant's preferred state (façade τv = one of five pre-selected settings).

* The difference between Scenario 2 and Scenario 3 consisted in that SC2 followed a fully bleached state and SC3 was achieved after a fully tinted setting of the façade.

Two experimental sequences of sessions were established (Order A and Order B), and they were randomly assigned to each participant (Fig. 2).

All sessions were run individually. At the start of the procedure, the participants were asked to sit at a desk positioned parallel to the west-facing window. The position of the chair was fixed via tape marks on the floor indicating its exact position. Subjects were asked to point their gaze at the screen of a 13.3-inch Dell XPS laptop computer (400-nits screen) located on the desk, where visual tasks and the questionnaire were presented (see Fig. 1). Participants were introduced to the

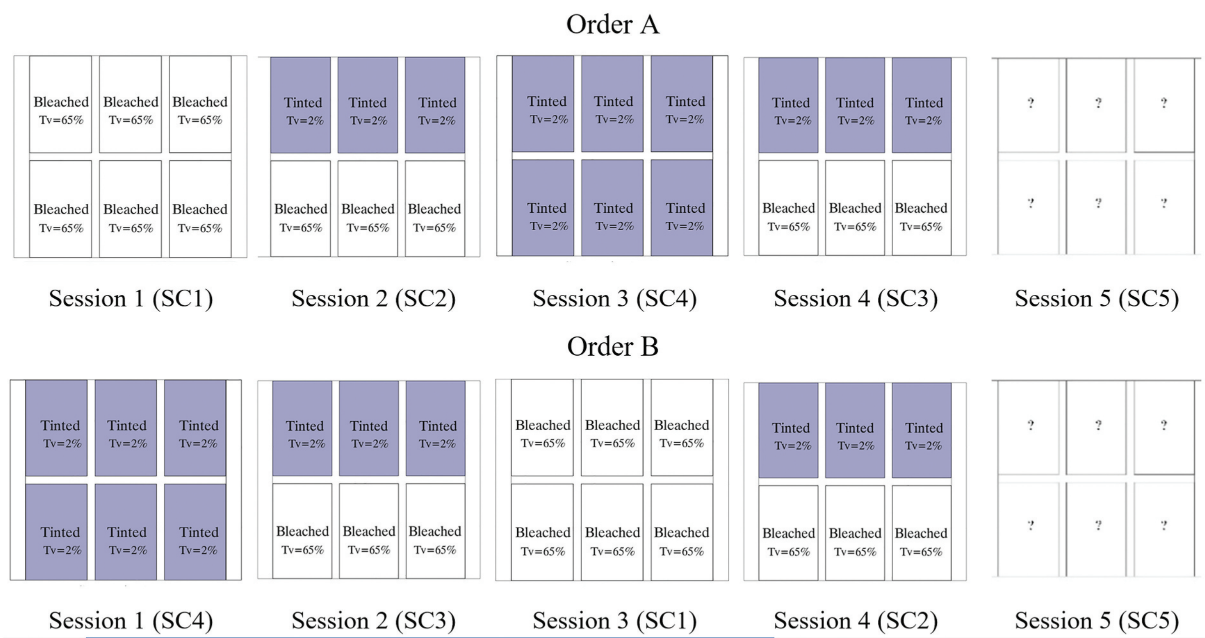


Fig. 2. Experimental sequences of EC glazing setting scenarios.

protocol, and the experimental procedure was explained in detail. Subjects were asked to fill an informed consent form and to complete a pretest questionnaire featuring basic demographic information (age, gender, background, etc.) and highlighting their current state of health and any eventual visual condition. Following this pretest process, the series of experimental sessions started, where the tint degree of the facade was manipulated by the experimenter – present at the back of the room, but outside the field of view of the participants – through a control panel situated on the wall opposite the view direction of subjects. While the EC glazing scenario was changed by the experimenter (SC1, SC2, SC3, or SC4), participants were asked to focus on a dummy visual task that was presented on the laptop monitor, without them being notified of the change.

Session 1 started with either SC1 (under Order A) or SC4 (under Order B), as shown in Fig. 2, based on a randomized Latin square sequence design that was counterbalanced across test participants. Before starting Session 5 (SC5), the experimenter introduced the test subject to the application "Cloud," which was installed on the mobile phone of the experimenter, to allow them to manually control the tint degree of the EC façade among five pre-selected states characterized by different global façade transmittance, respectively, τv = 65%, 31%, 15%, 8%, 2%. For all these pre-selected states, all the six EC panes were set to change at the same visible transmittance.

2.2. Measurements

Photometric measurements were taken by the experimenter during each session (Fig. 3). A Canon EOS 5D Mark II camera equipped with a fish-eye lens Sigma 8 mm F3.5 EX DG was used to produce High Dynamic Range (HDR) images for each state of the EC facade at the participants' eye level, ensuring adequate photometric and colorimetric accuracy (Cauwerts et al. 2019). The white balance setting and a sensitivity of ISO 100 was used to reduce the noise in the HDR images (Inanici 2006) and to maintain consistent color space transitions. A mid-range aperture size of f/11 was used as it has been found to produce relatively minimal vignetting and balance between an acceptable luminous range and lens flare effects (Jakubiec et al. 2016a). Since the experimental sessions were planned in days with mostly overcast sky to reduce extremes in high luminous ranges (vertical illuminance < 5000 lux), the neutral density ND filter was not used (Jakubiec et al. 2016a).

A sequence of 15 Low Dynamic Range (LDR) images with exposure time going from 1/8000

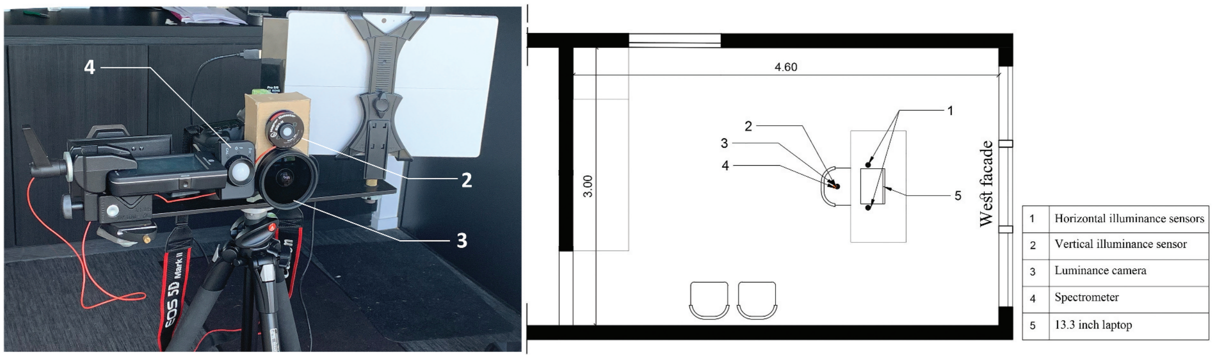


Fig. 3. Measurement equipment setup in the test room.

to 2 s were captured using the qDslrDashboard software (Hubai 2014) to remotely control the luminance camera and avoid any alignment problems within each sequence (Pierson et al. 2021). A Hagner Digital Luxmeter EC1 light sensor was placed just above the lens of the camera to record vertical illuminance (Ev) at eye level. A Konica Minolta LS-110 was used to take a luminance reading on a gray card target, with mid-range luminance, to calibrate the luminance map for each generated HDR image. The 15 LDRI-images were combined into a HDRI using the Photosphere software (Ward 2005) that was also used to calibrate the HDR images using the single-point reading captured by the luminance meter. The produced HDR images were later analyzed using the Evalglare software (Wienold and Andersen 2016) for average luminance L_{avg} and glare calculations.

A portable spectrometer, the CL-70F Konica Minolta CRI illuminance meter, was placed beside the camera lens to record the spectrum of the incoming daylight through the EC façade at the participants' eye level. The view angle of the device was set at the recommended 10° as it better correlates with the human eye's visual assessment of color, while also ensuring enhanced sensitivity in the blue part of the spectrum. This is particularly relevant when testing blue-tinted EC glazing (Jain and Wienold 2021). Two illuminance sensors Testo 540, calibrated to each other, were placed on the desktop, equally spaced at the right and left side of the participant, to measure average horizontal illuminance (E). A thermo-hygrometer Kestrel 5400 was used to record air temperature and relative humidity in the test room.

2.3. *Visual tasks and subjective assessments*

During each of the five sessions of the experimental procedure, participants were asked to perform a series of visual tasks and to fill in a questionnaire on the laptop screen.

A *letter searching* – using a short pseudo-text (Kent et al. 2017) – and a *typing* task – a generic text printed on a white A4 sheet of paper to be manually typed into a space on the computer screen – were presented to the participants as dummy tasks at the end of each session, while the setting of the EC façade was changed from one scenario to another. This was uniquely done to distract the participant from the changes in the glazing settings and to allow them to adapt chromatically to the different conditions (Arsenault et al. 2012; Logadóttir et al. 2013). Data from these two visual tasks (e.g., speed and accuracy) were not recorded nor included in the analysis.

After the change toward each EC setting scenario had been completed, the participants were asked to perform a *chromatic Landolt rings* task (Fig. 4), presented on the laptop screen, to examine visual acuity and color naming accuracy under different lighting conditions (Fotios and Cheal 2007; Liang et al. 2019, 2021).

The size of the Landolt rings was adjusted to meet the requirements of the visual acuity measurement standard test at 1 m distance on a computer screen (Consilium Ophthalmologicum Universale 1984). The chart presented 12 rows of Landolt rings with size decreasing from 8.0 M to 0.63 M (where the unit M specifies the height of typeset materials and is equivalent to 1.5 mm), decreasing in steps of 0.1 log unit per row (Liang et al. 2021).

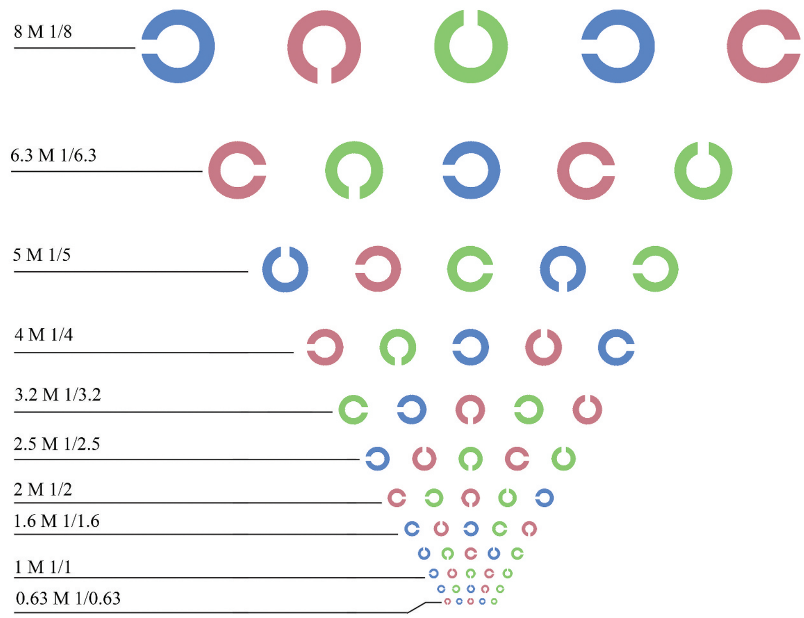


Fig. 4. Chromatic Landolt rings: standard measurements at 1 m distance. The colours of the rings are based on Fotios and Cheal (2007).

Each row contained five rings with at least one of each RGB color (red, green, blue) and gaps positioned in one of four permitted directions (up, down, left, right). The positions of each color in the chromaticity diagram were: red (x = 0.417, y = 0.315), green (x = 0.296, y = 0.491) and blue (x = 0.212, y = 0.226) (Fotios and Cheal 2007). Proceeding from the top to the bottom row, and from left to right, the participants were asked to name the color and the position of the gap for each Landolt ring. The responses were collected via a voice recorder for later sorting (Fotios and Cheal 2007). Visual acuity scores were analyzed as the number of errors in gap orientation, whereas the color naming accuracy was analyzed by the number of errors in rings' color. No time limit was assigned to this task (Liang et al. 2021). To avoid unwanted learning effects, the order of the Landolt rings was randomly changed under each EC scenario.

After having completed the Landolt rings visual tasks, while the EC glazing was still set at the given scenario, participants also provided their subjective assessment of visual perception by completing a questionnaire presented to them on the laptop screen. The design of the questionnaire was mostly based on the experimental methods proposed by Liang et al. (2019) to study human responses under colored glazing. Responses were collected via 7-point Likert scales using semantic bipolar anchor descriptors of the dependant variable. The questionnaire (fully reported in the Appendix (Table A.1)) featured groups of questions focusing on: interior light levels (Q1); visual task difficulty (Q2, Q3) (Liang et al. 2019); color appearance inside the room (Q4–9) (Clear et al. 2006; Jain et al. 2021; Liang et al. 2019); outside view (Q10–12) (Arsenault et al. 2012; Jain et al. 2021); color appearance of the glazing (Q13) (Clear et al. 2006; Zinzi 2006); and glare perception (Q14), using the 4-point Osterhaus' scale (Kent et al. 2017; Osterhaus and Bailey 1992). For each question, the subject was asked to choose the point on the scale, corresponding to a number from 1 to 7, that they felt best represented their visual perception under the current EC scenario. This allowed to treat the data as an interval scale (that is, scores have directionality and even spacing between them).

Each of the five sessions lasted 15 min, so as to keep the entire test, including the introductory session (10 min), and the presentation of the Cloud app (5 min), within a total of 90 min per participant.

2.4. Statistical analysis

Descriptive statistics were used to summarize luminous measurements for each EC scenario and are presented through boxplots and tables. Initial quantitative tests were run to verify if the data met the assumptions for performing parametric statistical analysis: the dependent variable needs to be measured at the continuous level (e.g., interval variables); the dependent variables should be normally distributed; the variances of the differences between all combinations of levels of the within-subjects factor must be equal; and, independence of observations, i.e., the data from different participants have to be independent (Field 2013; Field and Hole 2002). The within-subjects factor (independent variable) was the "EC façade setting" with five levels: fully bleached (SC1), mixed 1 (SC2), mixed 2 (SC3), fully tinted (SC4), and user control (SC5), where each of the five conditions was considered as a level.

Following the methodology suggested by (Field 2013; Field and Hole 2002), the tests of normality using Kolmogorov–Smirnov and Shapiro–Wilk tests, considering the distribution of each group, revealed that data of at least two levels of the within-subjects factor violated the assumption of normality ($p < .05$) for each dependent variable. The full inferential data is provided in the Appendix, Tables A2 and A3. Moreover, visual inspection of the boxplots and histograms revealed skewness in the data and the presence of outliers (boxplots are presented in the results section and in the Appendix). Since the assumption of normality was violated, and also the outliers seemed to present valid cases with no data entry or measurement errors, the non-parametric Friedman's ANOVA test was used (Field and Hole 2002). Also, the use of a 7-point Likert scale to collect the subjective assessments supported using the same non-parametric test, as suggested by the literature (Allen and Seaman 2007).

When significant differences between the groups could be detected by the Friedman's ANOVA, post hoc tests were run to determine where the variations laid under each condition. The Wilcoxon matched-pairs (or signed-rank) test was used (Wilcoxon 1992), which is the recommended post hoc test following the non-parametric Friedman's ANOVA (Field 2013; Field and Hole 2002; Pereira et al. 2015) as it accounts for non-normality by ranking the data (Wilcoxon 1992).

Bonferroni correction was applied in consideration of the experiment-wise error rate caused by the alpha level inflating across multiple tests carried out with the same hypothesis: corrected p = .05/number of comparisons (Cabin and Mitchell 2000; Maxwell and Delaney 2004). This was necessary since the same hypothesis was analyzed repeatedly across the multiple levels of the within-subjects factor (Cabin and Mitchell 2000). It should be noted that there could be unintended consequences of alpha-adjustment procedures using Bonferroni correction, as reducing the power of a statistical test (Pereira et al. 2015), while being dependent on both the size of the effect and that of the sample (Ellis 2010). Therefore, the emphasis of the inferential analysis was placed on the effect size (Ellis 2010). The effect size (r) was calculated to show whether the significant differences detected had any practically relevant magnitude and, therefore, provide more rigorous support to inferences. This was calculated by making use of equivalence between the standardized measure of the observed difference and the Pearson's coefficient r, by extrapolating the Zscore test statistic from the Wilcoxon matched-pairs tests, according to the following Equation 1 (Field 2013):

$$r = \frac{\mathrm{Zscore}}{\sqrt{\mathrm{N}}} \tag{1}$$

where N is the number of observations.

The magnitude of the effect size (r) was interpreted based on published benchmarks (Ferguson 2009): $r < 0.20$ = negligible; $0.20 \leq r < 0.50$ = small; $0.50 \leq r < 0.80$ = moderate; $r \geq 0.80$ = large.

3. Results

A total of 95 data points were collected by exposing 19 participants (7 females, 12 males) to five visual scenarios. Eight experimental tests were conducted in the morning hours (two at 9 am and six at 11 am) and 11 sessions in the afternoon (five at 1 pm and six at 3 pm). For each test, session 1 started with either SC1 (fully tinted) or SC4 (fully bleached) based on a randomized Latin square sequence design counterbalanced across test participants (Fig. 2). Among the 19 participants, 10 participants wore glasses or corrective lenses, all had a normal color perception.

The prevalent conditions were overcast and intermediate skies in compliance with their definitions by the CIE (International Commission on Illumination). For a few experimental sessions, unexpected direct sunlight through passing clouds briefly reached the interior of the test room (e.g., side walls), particularly during the afternoon tests, yet without falling on the desk surface or reaching the eyes of the participants (see Fig. A1 in the Appendix). Although some luminous measurements during these sessions led to outliers, as explained in the following sections, the data were retained since, as per the literature (Jakubiec et al. 2016a; Suk 2014), the measured illuminance did not reach levels that could be identified as high risk of visual discomfort. Luminance readings also ranged within the thresholds that are characteristic of the geographical location under overcast sky conditions (Ajaji and André 2015).

3.1. Indoor lighting conditions

Luminous measurements of the visual scene were taken immediately after each subjective assessment. Table 1 presents the descriptive statistics (mean, median, maximum, minimum, and standard deviation) for the following parameters: vertical illuminance; average horizontal illuminance on the desk from the two lux sensors; average luminance; and, DGP (Daylight Glare Probability) calculated from the HDR images. The complete boxplots of measured and calculated lighting conditions are provided as supplemental material in the Appendix (Fig. A2). Across all test sessions, the mean indoor temperature was 20°C (SD = 2.2°C) and the mean relative humidity was 40.7% (SD = 6.7%).

The accuracy of the HDR images was validated by comparing the vertical illuminance calculated from the HDRIs and that measured by the lux meter (Fig. 5). Four data points collected in one of the afternoon sessions in the presence of unexpected direct sunlight were characterized by a measured illuminance larger than the value derived from the HDR images. This might be explained by pixel overflow in the HDR images (Pierson et al. 2021). These images were corrected using the manual script suggested by Jakubiec et al. (2016b). The RSME between the calculated and measured values was 350 lux (normalized 7%), without consideration of the corrected images.

The measured luminous parameters directly related to the visible transmittance of the respective EC scenario: SC1 (fully bleached) presented the highest values, SC4 (fully tinted) corresponded to the lowest, while SC2 and SC3 were halfway between the two extremes. It is interesting to note that, although the SC2 and SC3 scenarios presented the same transmittance settings of all the EC panes, the respective luminous parameters

Table 1. Descriptive statistics for the luminous measurements under each EC glazing scenario.

Measurements	Scenario (N = 19)	Mean	Median	Max	Min	SD
Vertical illuminance (lux)	SC1	1366	1254	4560	80	994
	SC2	404	347	1359	62	314
	SC3	542	319	4977	42	1092
	SC4	115	49	1190	17	262
	SC5	654	574	1999	53	421
Average horizontal illuminance (lux)	SC1	1043	794	4544	89	1043
	SC2	244	199	819	43	193
	SC3	409	149	4795	29	1068
	SC4	53	26	429	11	93
	SC5	408	304	1315	19	288
Average luminance (cd/m^2)	SC1	441	404	1031	25	265
	SC2	142	144	455	24	104
	SC3	150	114	1054	14	229
	SC4	33	19	239	7	51
	SC5	244	181	902	18	218
DGP	SC1	0.25	0.25	0.43	0.02	0.08
	SC2	0.19	0.23	0.29	0.02	0.09
	SC3	0.17	0.22	0.58	0.01	0.14
	SC4	0.03	0.01	0.33	0.01	0.07
	SC5	0.22	0.22	0.40	0.01	0.08

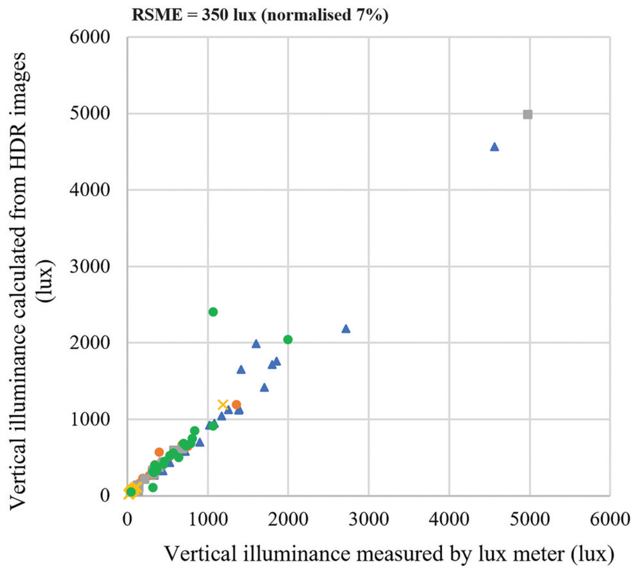


Fig. 5. Comparison of measured and HDRI-derived vertical illuminance for each scenario.

were mostly different, SC2 showing slightly higher values than SC3. It must be remembered that these two scenarios were achieved following a different previous setting: SC2 was set after a fully bleached state, SC3 after a fully tinted scenario. This could be due to technical reasons, leading to hypothesize that, in SC3, the three lower EC panes had not completed their switch to the fully bleached state, even about 10 min after the previous setting. For all scenarios, the mean and median calculated daylight glare probability was always DGP ≤ .25, corresponding to imperceptible glare according to the European standard EN17037 (CEN 2019).

Table 2 presents in detail the breakdown of descriptive statistics for the scenarios corresponding to the setting of the EC façade chosen by the participants (SC5). Data outliers were recorded in two sessions due to higher levels of illumination received from direct sunlight through passing clouds. The complete boxplots for the illuminance and luminance data are provided as supplemental material in the Appendix.

3.2. Measurements of light spectra

The spectral composition of the daylight filtered through the different settings of the EC façade was recorded throughout the experimental procedure, covering the range from 380 to 780 nm. The outputs of the median SPD (spectral power distribution) for each interval wavelength between 380 and 780 nm and the normalized median SPD for each interval wavelength (peak equals 1), for scenarios SC1 to SC4, are presented in Fig. 6. The normalized curves are plotted to evaluate the shape of the spectra and describe the "naturality" of the incoming daylight from each of the pre-set EC glazing scenarios compared to the CIE standard D55 daylight illuminant (Mardaljevic et al. 2014) generated using the TM-30 tool (Houser et al. 2022). The descriptive statistics for the resulting CCT (correlated color temperature) and CRI (color rendering index) are shown in Table 3. Figure A3 in the Appendix presents an example of the measured chromaticity coordinates under each scenario.

The median SPD normalized curves show a pronounced peak in the blue part of the spectrum at around 460 nm, particularly for the fully tinted setting (SC4). This may interfere with the

Table 2. Detailed descriptive statistics for the luminous parameters selected under user control (SC5).

SC5 Measurements (*N* = 19)	τ_v% (frequency)	Mean	Median	Max	Min	SD
Vertical illuminance (lux)	65% (6)	899	715	1999	321	592
	31% (10)	580	500	1068	319	241
	15% (1)	Absolute value = 332				
	8% (1)	Absolute value = 53				
	2% (1)	Absolute value = 837				
Average horizontal illuminance (lux)	65% (6)	548	450	1315	231	406
	31% (10)	406	344	785	209	182
	15% (1)	Absolute value = 169				
	8% (1)	Absolute value = 19				
	2% (1)	Absolute value = 204				
Average luminance (cd/m^2)	65% (6)	396	223	902	104	337
	31% (10)	196	173	335	113	75
	15% (1)	Absolute value = 108				
	8% (1)	Absolute value = 18				
	2% (1)	Absolute value = 162				

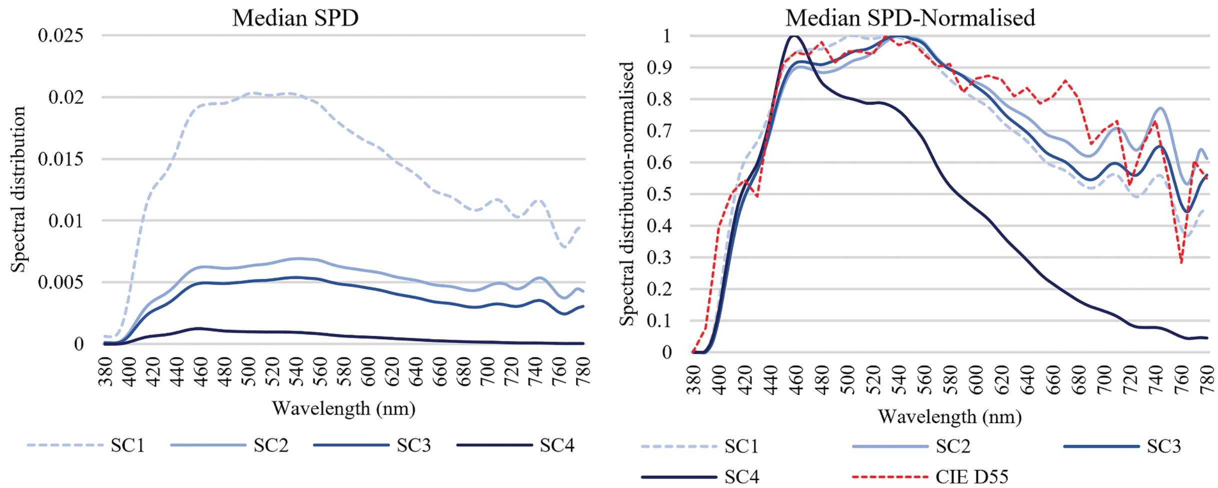


Fig. 6. Median light spectra for each interval wavelength (left) and normalized curves (including CIE D55) (right) for SC1, SC2, SC3 and SC4.

Table 3. Descriptive statistics for the CCT and CRI under each EC glazing scenario.

	Scenario N = 19	Mean	Median	Max	Min	SD
CCT (K)	SC1	5780	5655	6698	5081	504
	SC2	5340	5420	5838	4722	311
	SC3	5749	5594	7569	4934	576
	SC4	9570	9107	12963	7293	1490
	SC5	6426	6105	9057	4716	1083
CRI %	SC1	95.0	95.1	96.7	92.5	1
	SC2	93.2	92.9	95.2	91.7	0.9
	SC3	91.9	92.2	94	85.1	1.9
	SC4	84.4	84.3	86.2	82.9	0.9
	SC5	90.1	89.7	95.3	83.5	3.7

natural rendition of objects' color inside the room, evoking concerns of user acceptance, as emphasized by previous studies (Arsenault et al. 2012; Mardaljevic et al. 2016). This is also supported by the values of CCT (Mean = 9570, Mdn = 9107) and CRI (Mean = 84.4%, Mdn = 84.3%), which, respectively, increase and decrease as the EC glazing is set to its full deep blue tint. As a comparison, the CCT of CIE standard illuminants D55 and D65 is, respectively, 5499 and 6500 K. However, the measured CRI_{min} remains consistently higher than 80%, which is the minimum value recommended to provide an acceptable reproduction of colors (Piccolo et al. 2009).

For the mixed scenarios, SC2 and SC3, the normalized curves appear fairly neutral (particularly with respect to CIE D55) with no pronounced shift to the blue part of the spectrum, in agreement with Mardaljevic's theoretical model for a combination of bleached and tinted EC panes (Mardaljevic et al. 2016). The measured CCT (Mdn SC2 = 5420, Mdn SC3 = 5594) and CRI (Mdn SC2 = 92.9%, Mdn SC3 = 92.2%) support this finding. Graphical inspection of the normalized curves of SC2 and SC3 also shows that, with respect to the fully bleached scenario (SC1), there is a suppression of wavelengths shorter than 540 nm, and an enhancement of wavelengths longer than 540 nm. The resulting CCTs (Mdn SC2 = 5420; Mdn SC3 = 5594) were lower than the fully bleached setting (Mdn SC1 = 5655). This observation can be interpreted by the difference in the contribution of diffuse light from the sky in the mixed scenarios SC2 and SC3 compared to the fully bleached EC façade (SC1). In fact, although the mixed scenarios SC2 and SC3 have an equivalent global visible transmittance of around 32.5% (that is, τv 65%+2%/2), about 97% of the incoming light is due to contribution from the three bottom panes that are set to their bleached state, whose view angles are more oriented toward the ground

(Mardaljevic et al. 2016). This might have caused a more significant influence of the light reflected off the surrounding landscape with respect to the contribution from the sky component transmitted through the three upper panes in their fully tinted state.

3.3. Visual task performance

For the chromatic Landolt rings task performed by test participants under the five EC scenarios, Table 4 and Fig. 7 show, respectively, the descriptive statistics and the boxplots of the Friedman's ANOVA tests for the number of errors in the visual acuity (gap orientation) and color naming accuracy (rings' color) data.

In agreement with the literature (Liang et al. 2021), the descriptive statistics show that identifying the gap orientation in the Landolt rings (visual acuity) seemed to be more challenging than the rings' colors (color naming accuracy), as revealed by the number of incorrect responses. However, the Friedman's ANOVA tests did not detect any significant differences in the errors of visual acuity (χ^2 (4) = 3.99, $p > .05$) and color naming accuracy (χ^2 (4) = 3.27, $p > .05$) between the five EC scenarios. This result suggests that visual task performance was not significantly affected by changing the setting of the EC glazing façade, as measured using the chromatic Landolt ring task.

3.4. Visual perception

Subjective assessments of perceived light conditions were collected and analyzed under each EC façade setting. Participants' evaluations included

Table 4. Descriptive statistics for the chromatic Landolt rings task.

Visual Task Performance	Scenario (*N*=19)	Median	Mode	Max	Min
Number of errors in gap's orientation	SC1	6.0	6.0	10.0	4.0
	SC2	6.0	9.0	16.0	2.0
	SC3	6.0	5.0	11.0	2.0
	SC4	7.0	5.0	13.0	3.0
	SC5	6.0	4.0	11.0	4.0
Number of errors in rings' color	SC1	0.0	0.0	9.0	0.0
	SC2	0.0	0.0	5.0	0.0
	SC3	0.0	0.0	5.0	0.0
	SC4	1.0	1.0	6.0	0.0
	SC5	0.0	0.0	8.0	0.0

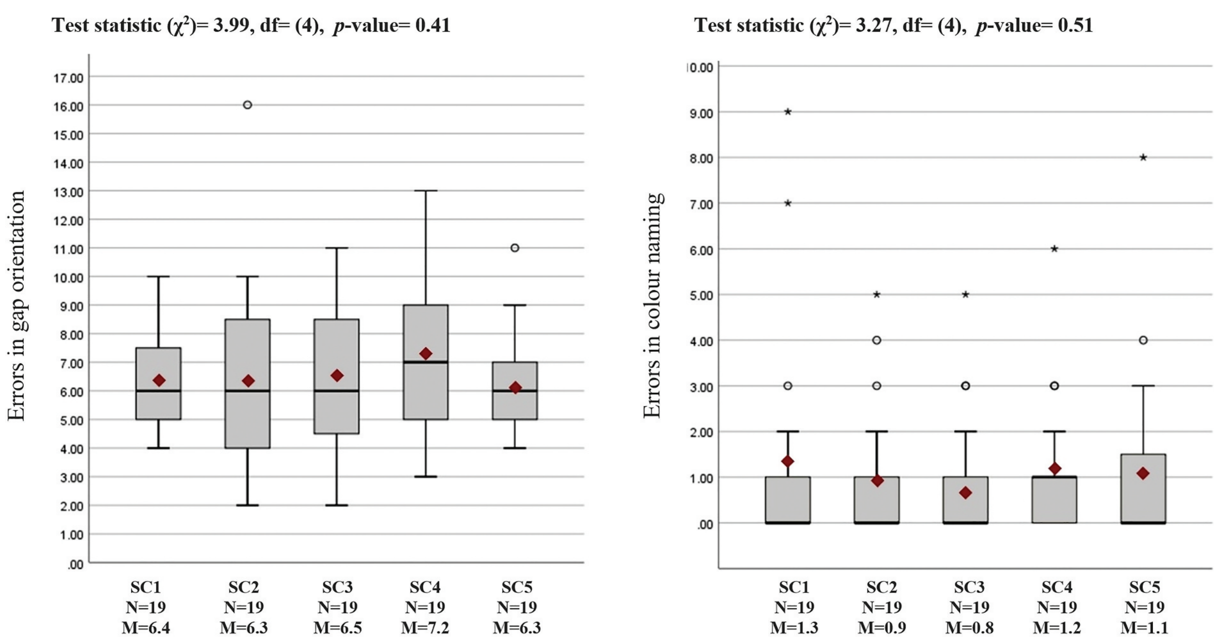


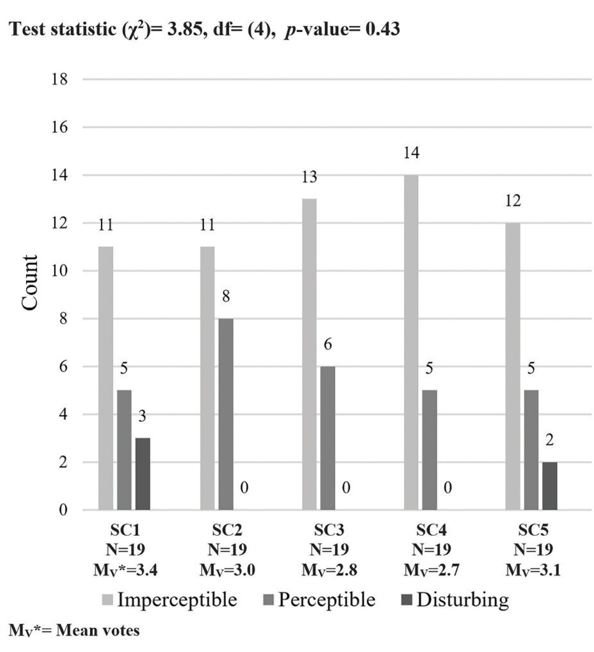
Fig. 7. Boxplots of the number of errors in gap orientation (left) and colour naming accuracy (right).

reporting their assessment of discomfort due to glare. Figure 8 shows the results of the statistical tests and the frequency of participants' glare perception votes collected on the 4-point Osterhaus scale (imperceptible, perceptible, disturbing, intolerable) for each EC scenario (left) and the boxplots of DGPs calculated from the HDR images (right). No significant differences were detected in glare responses from the various EC settings ($\chi^2(4) = 3.85$; $p > .05$) and the frequency of evaluations showed a similar general trend of imperceptible glare as the mean DGP values calculated from the HDR images ($N = 61$ (frequency = 64%); Mean DGP consistently lower than 0.35). This result could be expected considering that the experimental tests were performed mostly under overcast sky conditions. Yet, 31% of the participants' responses reported perceptible glare ($N = 29$), and 5% indicated luminous situations causing disturbing glare ($N = 5$). No evaluations of intolerable glare conditions were recorded.

For the subjective assessment of lighting conditions, the Friedman's ANOVA test was used to analyze the differences in participants' responses across the five EC scenarios. Table 5 presents the results of the statistical tests emphasizing, in the first column, the variable that was measured through the questionnaire (the full text of the questions is available in the Appendix, Table A.1). For 12 out of 14 questions, the ANOVA test detected statistically significant differences across the different settings of the EC façade. Wilcoxon matched-pairs signed rank post hoc tests were used to identify where the differences detected laid. The results are presented in the following sections.

3.4.1. Daylight levels

Perception of daylight levels in the room (Q1) was found to be significantly different across the five EC settings ($\chi^2(4) = 39.50$, $p = .000$; see boxplots in Fig. 9). The Wilcoxon signed rank test was used to run comparisons between paired scenarios and look for differences in the ranked positions of scores in the two conditions (Field and Hole 2002). Table 5 presents the results of the pairwise comparisons, providing the mean, standard deviation, median, interquartile range, differences in mean and median, positive and negative differences between the ranks, the ties, the associated test statistic (Zscore) and statistical significance (p-value) for the Wilcoxon matched-pairs test, and the effect size (r). Since the test statistic Z is set to equal the smaller of the sums of ranks (positive or negative), it has always lower values than the average ranks (King and Eckersley 2019; Sawilowsky and Salkind 2007). Therefore, the Zscore is consistently negative as is the effect size, which has to be interpreted in its absolute value (Kent et al. 2016). The



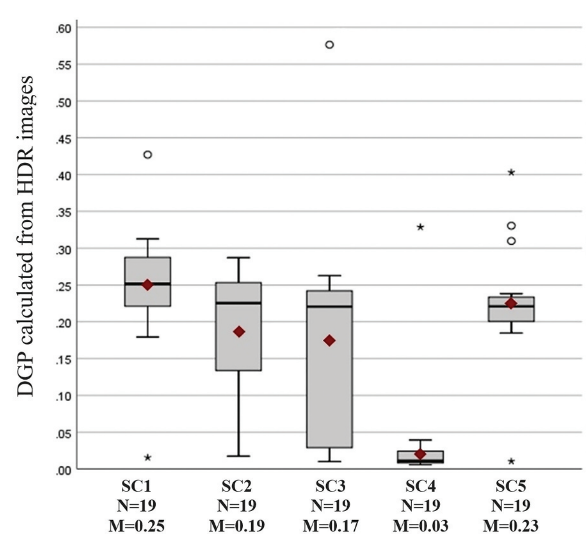


Fig. 8. Subjective assessment of glare perception (left); boxplots of DGP calculated from the HDR images (right).

Table 5. Friedman's ANOVA tests for all the responses to the questionnaire.

Variable	Test statistic (χ²), df=(4)	*p*-value
Q1. Perception of daylight levels in the room	39.50	.000***
Q2. Self-assessed visual performance: color naming accuracy	9.10	.059 n.s.
Q3. Self-assessed visual performance: gap orientation	10.90	.028*
Q4. Perception of color appearance of internal room surfaces	26.24	.000***
Q5. Perception of color appearance of the white paper	32.65	.000***
Q6. Perception of color appearance of the computer screen	18.34	.001**
Q7. Perception of color appearance of skin and clothes	36.64	.000***
Q8. Perception of color appearance of the overall lighting inside the room	51.89	.000***
Q9. Satisfaction with color appearance of the lighting inside the room	36.38	.000***
Q10. Perception of color appearance of external surfaces and objects	36.79	.000***
Q11. Perception of color appearance of the external view	35.09	.000***
Q12. Satisfaction with color appearance of the external view	33.71	.000***
Q13. Perception of color appearance of the glazing	23.91	.000***
Q14. Evaluation of glare sensation from the window	3.85	.426 n.s.

$p \leq .001$ = highly significant***; $.001 < p \leq .01$ = significant**; $.01 < p \leq .05$ = weakly significant*; $p > .05$ = not significant (n.s.)
Shaded cells show the detection of statistically significant differences.

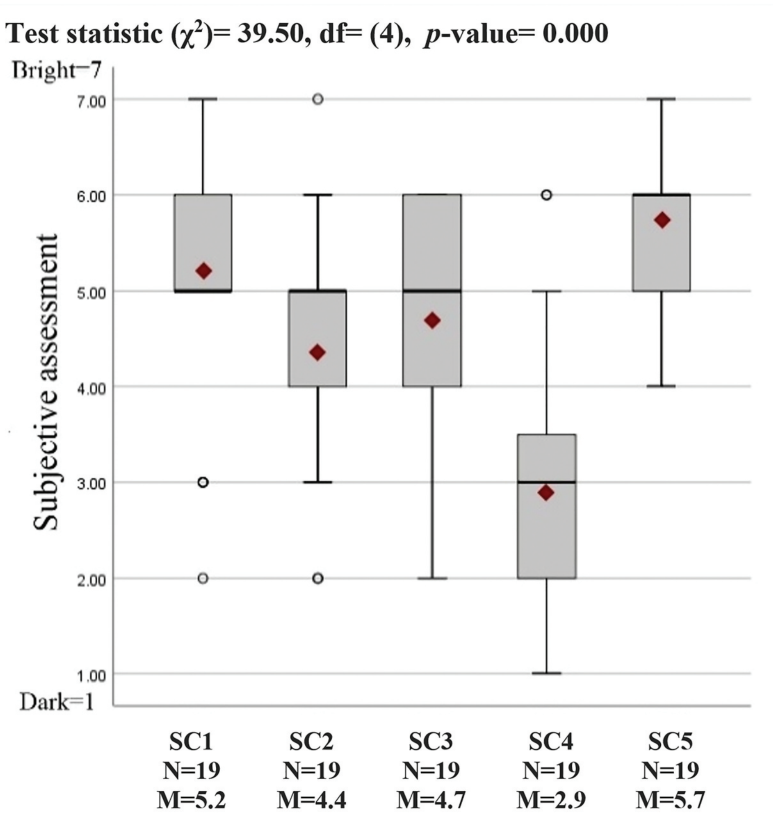


Fig. 9. Boxplots of subjects' assessment of indoor daylight levels under the five EC scenarios.

directionality of the difference between groups can be ascertained by inspection of descriptive statistics and of the boxplots.

The post hoc analysis detected consistently significant differences in subjective ratings between SC4 and all other scenarios, with moderate effect sizes ($p < .005$, $0.50 \leq r < 0.80$). This indicates that the light levels from the fully tinted façade (SC4) were rated substantively lower than all the other scenarios, as also revealed by the sign of ΔMdn. When the mixed scenarios SC2 (set after the fully bleached state) and SC3 (set after the fully tinted state) were compared to the fully bleached state (SC1), subjective ratings of indoor daylight levels were lower, with moderate (SC1 vs. SC2, $p = .002$, $r = -0.50$) and small effect sizes (SC1 vs. SC3,

$p = .124$, r = −0.25), although the latest comparison was not statistically significant. Differences in perception of lighting levels under the two mixed scenarios were not statistically nor practically relevant (SC2 vs. SC3, $p = .233$, r = −0.19). When the pre-set scenarios were compared to the user-controlled setting (SC5), subjective ratings were consistently higher for SC5 (negative ΔMdn across all comparisons), with differences having statistical and practical relevance for the contrasts with SC2 and SC4 ($p < .005$, $0.50 \leq r < 0.80$). When SC5 was compared with the fully bleached setting (SC1) and the SC3 scenario, the differences in subjective ratings of indoor lighting levels were substantive (r = −0.21 and r = −0.44, respectively), but not statistically significant.

3.4.2. Self-assessed task performance

The Friedman's ANOVA tests revealed a significant difference in subjective assessments of task performance difficulty while identifying the gap's orientation in the Landolt rings (Q3) across the various EC glazing scenarios ($\chi^2(4) = 10.90$, $p = .028$). Conversely, no significant differences were detected for self-assessed task performance difficulty related to the color naming accuracy (Q2) ($\chi^2(4) = 9.10$, $p = .059$). Post hoc analysis using the Wilcoxon signed-rank matched-pairs test was run for Q3 responses and the results are presented in Table 7. The boxplots of the data concerning self-assessments of visual task difficulty are presented in the Appendix (Fig. A4).

The Wilcoxon matched-pairs test detected several effects of practically relevant magnitude, although the contrasts were consistently not statistically significant across all comparisons ($p > .005$). This might be due to the conservative nature of the alpha-adjustment procedure using Bonferroni correction in relation to the number of levels of the within-subjects factor and the experiment-wise error rate caused by the alpha-level inflating across multiple pairwise comparisons (Cabin and Mitchell 2000; Ellis 2010). The estimation of effect sizes (also looking at the values of ΔMean and ΔMdn) detected substantive influences for multiple comparisons, particularly for those that compared evaluations given under SC5 against SC1, SC3, and SC4 (respectively, r = −0,26, r = −0.36, r = −0.43). Substantive influences were also found when comparing SC2 vs. SC3 (r = −0.38) and vs. SC4 (r = −0.35). These results lead to infer a tendency for slightly higher subjective ratings when evaluating the "easiness" of color naming accuracy under the SC2 (mixed after bleached) and SC5 (user controlled) scenarios compared to other settings. Interestingly, this evaluation was made despite of the lower lighting levels measured under SC2 and SC5 compared to the bleached state SC1 (Table 1).

3.4.3. Colour appearance of the internal environment

The Friedman's ANOVA tests detected statistically significant differences between participants' responses to all the questions concerning the perception of color appearance of the internal environment (Q4–Q8), and their satisfaction with indoor lighting (Q9), across the various settings of the EC façade (Table 5). The results of the post hoc analysis using Wilcoxon matched-pairs tests is shown in Table A4 in the Appendix.

For the responses to Q8 and Q9 on, respectively, perception and satisfaction with color appearance of indoor lighting, Fig. 10 presents the boxplots of the statistical data under the five EC scenarios. The boxplots for all the comparisons related to questions Q4–Q7 are provided as supplemental material in the Appendix (Fig. A5).

The pairwise comparisons between the fully tinted scenario (SC4) and all other settings of the EC façade detected significant differences between subjects' perception of indoor colors – i.e., internal surfaces (Q4), white paper (Q5), figures and text on the computer screen (Q6), subjects' skin and cloths (Q7), and internal lighting (Q8) – in 15 out of 20 cases ($p < .005$). For all these contrasts, effects had practically relevant values, ranging from r = −0.27 to r = −0.61. For satisfaction with the color appearance of indoor lighting (Q9), participants were consistently less satisfied with the SC4 scenario, with effects of statistical significance in three out of four cases, and substantive magnitude ($-0.40 < r < -0.58$). Overall, the color appearance of the indoor light with the façade in its fully tinted state was rated the least acceptable (Q8) and the least satisfying (Q9) compared to other scenarios. These results support previous findings (Clear

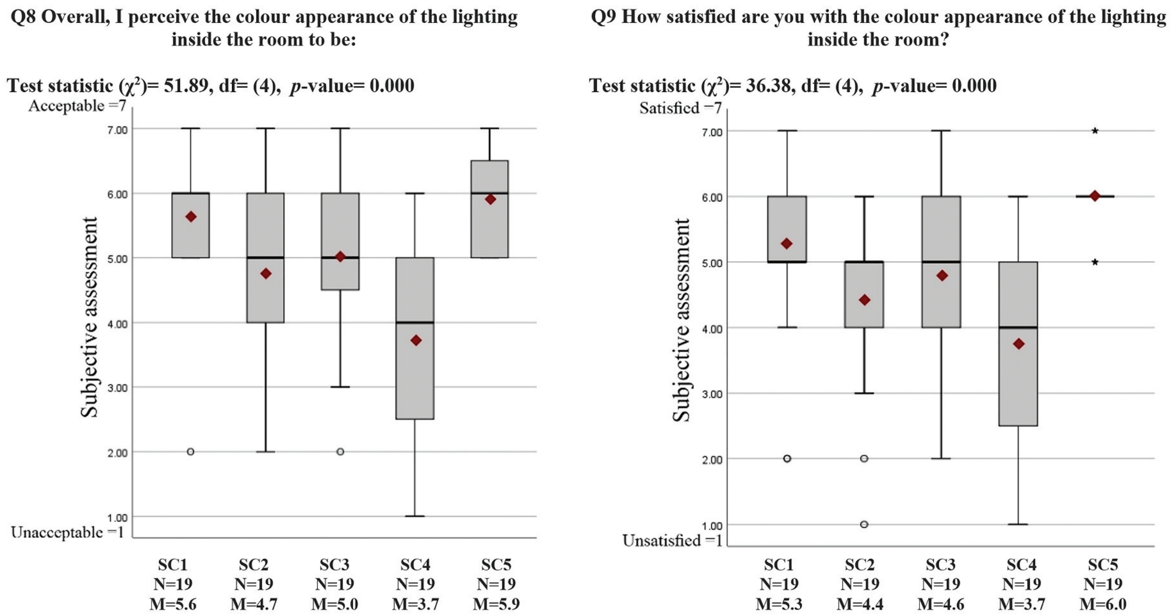


Fig. 10. Boxplots of the responses to Q8 and Q9 concerning subjective acceptance and satisfaction of internal lighting colour appearance.

et al. 2006; Jain et al. 2021) of lower subjective acceptance associated with the colored state of EC glazing.

For the mixed scenarios, pairwise comparisons between SC2 and the bleached state SC1 detected significant differences for Q4, Q5, Q7, and Q8 with effects of substantive magnitude ($-0.46 < r < -0.57$), suggesting better color perception with the EC glazing in its bleached state. Remarkably, comparisons between SC1 and the mixed scenario SC3 did not lead to detect any significant influences, nor did the contrasts between SC2 and SC3, although effects sizes were still mostly ranging between small and moderate. For these comparisons, the sign of the effects sizes, and of ΔMean and ΔMdn, lead to postulate a higher acceptance of color appearance under SC1 compared to SC3, and under SC3 compared to SC2. It should be remembered, however, that SC3 was presented to participants after the fully tinted scenario, this suggesting the hypothesis that a potential "memory" effect could have biased these evaluations.

For the user-controlled scenario SC5, no significant differences were detected across questions Q4-Q8 when pairwise comparisons were made against evaluations provided under the bleached state SC1 and the mixed scenario SC3. Conversely, significant differences of substantive effect sizes ($-0.35 < r < -0.63$) were detected when SC5 was compared to SC2 and SC4. In general, the color appearance of indoor lighting was rated the most acceptable (Q8) and most satisfying (Q9) under SC5 compared to all other scenarios, reinforcing once again the importance of perception of environmental control in subjective evaluations (Day et al. 2019). For questions Q6, requesting participants to describe the color appearance of figures and text on their computer screen, significant differences could only be detected when comparing the fully tinted (SC4) scenario and the user-controlled setting (SC5) ($p = .003$, $r = -0.49$). This result supports the idea that self-illuminating visual tasks might be less directly impacted by the switching strategy of an EC glazing (Mardaljevic et al. 2016).

3.4.4. View to the outside

The Friedmans' ANOVA detected statistically significant differences between responses for questions Q10–Q12 – on perception and satisfaction with the external view – across the five EC glazing scenarios (Table 5). The results of the post hoc analysis using Wilcoxon signed rank matched-pairs tests are shown in Table A5 in the

Appendix, and boxplots of statistical data are presented in Fig. 11.

The responses showed that the color appearance of external surfaces and objects (sky, trees, etc.) (Q10), and perception and satisfaction with the color of the external view in general (Q11 and Q12, respectively), were rated the least natural under the fully tinted facade (SC4), particularly when compared against the fully bleached scenario (SC1) and the user-controlled setting (SC5). All these pairwise comparisons showed statistically and practically relevant effects of moderate magnitude ($-0.54 < r < -0.60$). For the mixed scenarios, statistically significant differences were detected when comparing the perception of the external environment across the bleached (SC1) and the SC2 mixed state. Participants, in this contrast, expressed higher ratings for the bleached scenario ($p = .001$, $r = -0.54$), an evaluation that is consistent also with the results for other questions, although the practically relevant effects detected ($r = -0.46$ for Q11, $r = -0.43$ for Q12) were marginally not statistically significant. Comparisons between the two mixed scenarios, SC2 and SC3, did not lead to the detection of significant effects under these questions, although a tendency for higher rating

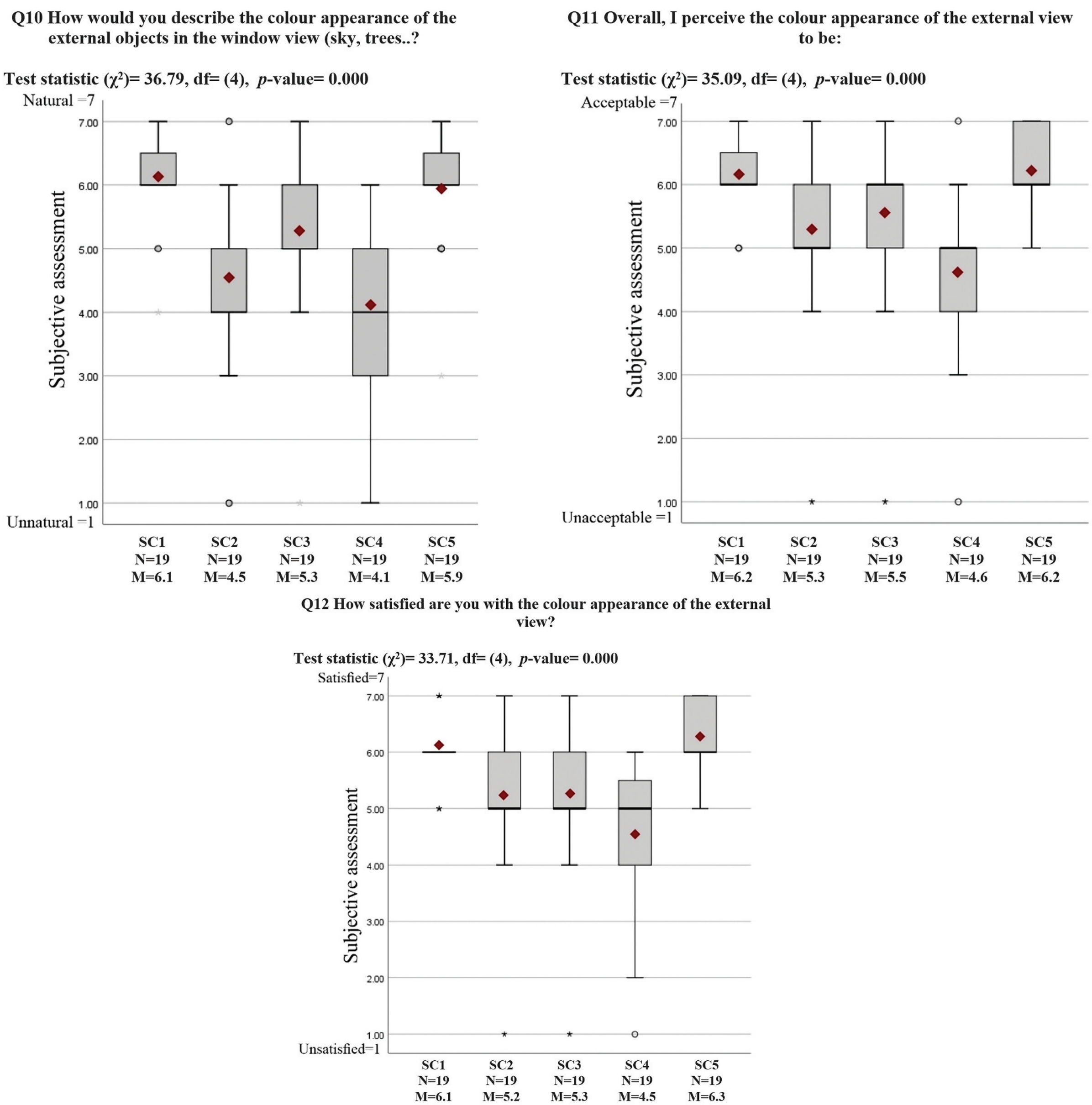


Fig. 11. Boxplots of the responses to questions 10, 11 and 12 concerning subjective assessment of the external view.

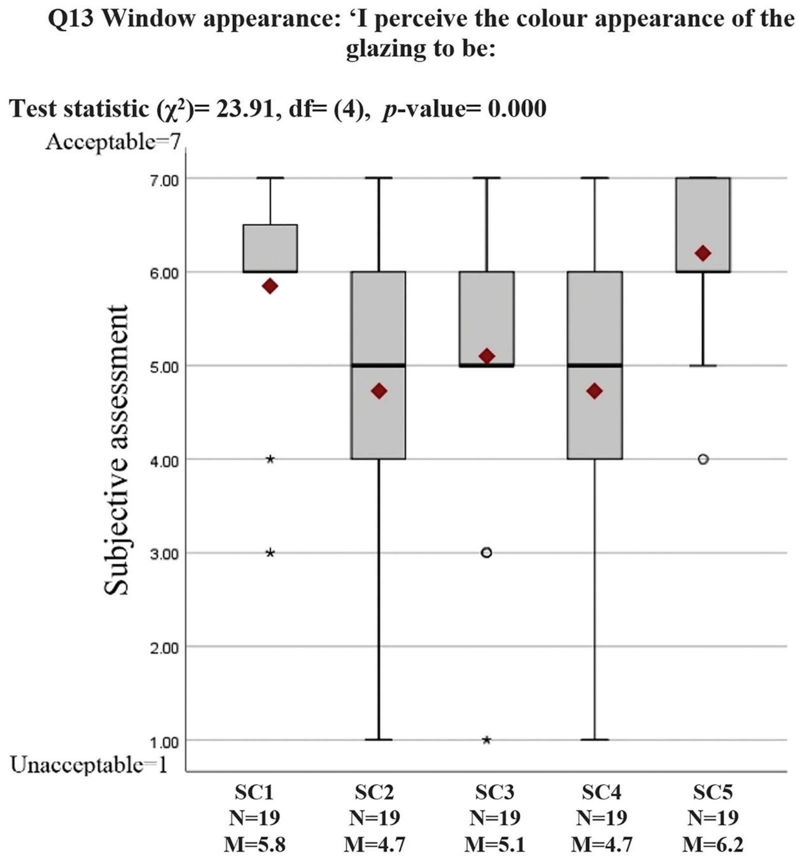


Fig. 12. Boxplots of subjects' assessment of the colour appearance of the glazing

expressed under SC3 could be postulated by the inspection of effects sizes (r = −0.43 for Q11, *r* = −0.27 for Q12) and the signs of ΔMean and ΔMdn. As for the evaluations given for the color appearance of internal objects, the experimental procedure might have biased such outcome, as SC3 was always presented after the glazing had been set to its fully tinted state. These results, therefore, reinforce the hypothesis that different subjective assessments under the mixed scenarios could depend on the previous state of the EC façade. Finally, no differences in perception and satisfaction of statistical nor practical relevance could be detected when the user-controlled scenario (SC5) was compared to the bleached setting (SC1). Conversely, SC5 was consistently rated more natural with respect to the fully tinted scenario across the three questions ($p < .001$, $r = -0.54$, −0.56 and −0.60, respectively), and also against the mixed scenarios SC2 (for Q10; $p = .003$, $r = -0.49$)) and SC3 (for Q12; $p = .004$, $r = -0.46$). This indicates that the color appearance of the external environment under user control was perceived more acceptable and satisfactory compared to other settings. However, it should be noticed that subjects' selections of the tint degree of the EC façade (τ_v mostly ranging between 65% and 31%, see Table 2) could have influenced this evaluation.

3.4.5. Colour appearance of the glazing

The Friedman's ANOVA detected statistically significant differences between participants' responses to Q13 concerning user acceptance of the color appearance of the glazing across the five EC scenarios (Table 5). The results of the Wilcoxon signed-rank matched-pairs tests are shown in Table 8. Figure 12 shows the boxplots of the statistical data for the subjective evaluations.

The Wilcoxon signed-rank tests detected effects of small magnitude for the pairwise comparisons between the bleached setting of the façade (SC1) and the mixed (SC2 and SC3) and fully tinted (SC4) scenarios ($-0.30 < r < -0.42$). The contrasts were not statistically significant, although inspection of descriptive statistics (e.g., the signs of

ΔMean and ΔMdn) leads to postulate a higher acceptance of the color appearance of the glazing when the façade was set to its clear state. Conversely, when the bleached state (SC1) was compared against the user-controlled scenario (SC5), a small – yet, not statistically significant – influence could be found, suggesting a higher acceptance of the color of the glazing for SC5. Similarly, when the setting of the EC façade selected by participants was compared against the SC3 mixed scenario, and the fully tinted façade (SC4), statistical and practical significance was detected ($p < .003$, $-0.49 < r < -0.52$).

4. Discussion

This experimental study was designed to explore whether dynamic changes in the spectral composition of daylight filtered through an EC façade can influence users' visual task performance and visual perception, contextualizing the results within the evidence from previous research (Clear et al. 2006; Jain et al. 2021; Mardaljevic et al. 2016). Subjective assessments were sought in relation to acceptance and satisfaction with the indoor (i.e., indoor daylight levels, color appearance of internal objects and surfaces, of the lighting, and of the glazing) and the outside luminous environment (i.e., color appearance of objects in the external view). The interpretation of the findings is presented in the following paragraphs.

The results showed no significant differences in the number of errors for visual acuity (gap orientation) and color naming accuracy (ring's color) in a chromatic Landolt rings task across the five different setting scenarios of the EC façade (Fig. 8). This indicates that dynamic changes in the spectral composition of the daylight through different states of the EC glazing did not significantly affect *visual task performance*. This result is consistent with previous research conducted under artificial light that was varied in illuminance and spectrum (Boyce et al. 2003), and with experimental testing performed under dynamic lighting (Kompier et al. 2021). Although inspection of statistical distributions for visual task performance (means and medians of errors) revealed a tendency for the identification in gap orientation being more challenging than color recognition (Table 4), no practically relevant evidence could be found of increased participants' alertness at higher color temperatures (Shamsul et al. 2013). This was also confirmed by participants' self-assessments of the task difficulty for visual acuity and color naming accuracy, which did not detect any statistically significant differences among the EC glazing scenarios (Table 7). Yet, it should be considered that EC settings with higher CCT of incoming daylight (SC4 and SC5), also corresponded to lower levels of vertical and horizontal illuminance (see Tables 1 and 3). In general, the findings on visual performance should be treated with caution due to the relatively low level of cognitive engagement required by the chromatic Landolt rings task, and also based on the consideration that color naming accuracy could be considerably impacted when involving other tints of the glazing (i.e., bronze, green), as shown in the literature (Chen et al. 2019; Liang et al. 2021).

The results from the analysis of the visual perception questionnaires are generally in line with the findings from previous studies that have analyzed user acceptance of deep-tinted glazing and lighting characterized by high color temperature (Arsenault et al. 2012; Clear et al. 2006; Day et al. 2019; Jain et al. 2021). However, before discussing in detail the outcomes of the subjective assessments, it should be noted that the evaluation of the internal and external environment was given by participants based on pre-set scenarios that were independent of effective sky luminance. Under normal operation, the EC glazing would be less likely to be adjusted to its fully tinted state under the sky types selected for this study (i.e., overcast and intermediate), since these conditions are generally associated with lower risks of solar overheating or discomfort due to glare. This is also confirmed by the selection of EC tint degrees within the user-controlled scenario (SC5), mostly ranging between $\tau v = 65\%$ and $\tau v = 31\%$ (Table 2). However, even under an overcast sky, when given control, only 32% of participants kept the EC glazing at its fully bleached state, this suggesting that the preference for the operation of a dynamic façade might be independent from the effective presence of the sun in the field of view of an observer, or the clear detection of a direct or indirect source of luminous or thermal discomfort.

Also, in a real-world setting, the responses provided under each EC scenario might differ depending on actual sky conditions as, for example, an overcast sky seen through deep blue tinted glass might not evoke the same perception as the view of a blue sky with the contribution of direct and/or ambient sunlight (Mardaljevic et al. 2016). Also, in case of high sky luminance, internal illuminance levels could be more acceptable than the lighting conditions monitored in this study under the fully tinted scenario (Table 1).

Despite this intrinsic constraint of the experimental procedure – necessary for the scenarios to be comparable and to avoid occurrence of direct sunlight in the field of view of the participants – the results from this study provide statistical evidence that the *daylight availability* within the room was perceived to be significantly different between the five EC settings, with ratings for the fully tinted scenario (SC4) that were substantively lower (that is, darker) than for all other settings (Table 6). In terms of *color appearance* of the internal and external environments and of the indoor lighting, participants were consistently less satisfied with the fully tinted (SC4) glazing scenario (Tables A4 and A5 in the Appendix). This finding supports results from previous studies showing lower acceptance associated with the deep blue tint of the EC glazing (Clear et al. 2006; Jain et al. 2021). The bleached state of the EC façade (SC1) was considered to provide a better color perception than the mixed settings (SC2 and SC3), although the scenarios combining bleached and tinted EC panes improved the "naturality" of the incoming daylight compared to the fully tinted façade (Mardaljevic et al. 2014, 2016). This finding from the subjective assessments was also confirmed by light spectra measurements (Table 3) and the evaluation of the shape of SPD normalized curves of SC2 and SC3 (Fig. 3). This might also be due to the configuration of the mixed EC façade adopted in this study – with the three upper panes fully tinted (view angle toward the sky) and the three bottom panes fully bleached (view angle toward the landscape) – resulting in a slight suppression of wavelengths shorter than 540 nm and enhancement of wavelengths longer than 540 nm compared to the bleached state. The CCT was also lower in the case of the mixed scenarios compared to the fully bleached setting (Table 3), leading to postulate a higher contribution from the light reflected off the landscape and external ground with respect to the diffused skylight. Nonetheless, compared to the fully tinted façade, the mixed scenarios had sufficient visible transmittance ($\tau v = 33.5\%$) in terms of daylight distribution (e.g., horizontal illuminance) (Boyce et al. 1995), better subjects' ratings in terms of satisfaction and acceptance of the lighting, yet offering glare protection from high angle sun or sky luminance (Jain et al. 2022) without excessively compromising internal and external color appearances.

With respect to the mixed scenarios, it is interesting to highlight that differences could be found both in measured light levels (Table 1) and in the comparisons of subjective assessments between settings with fully bleached or fully tinted façade and the responses given under scenarios SC2 and SC3, although these had the same glazing configuration and transmittance. It should be considered that the mixed scenarios were presented

Table 6. Results of the Wilcoxon signed-rank tests for the subjective assessment of indoor daylight levels (Q1).

Pairwise comparison	Mean 1 (SD)	Mean 2 (SD)	ΔMean	$M_{dn}1$	$M_{dn}2$	ΔM_{dn}	IQR1	IQR2	Positive	Negative	Ties	Test statistic	*p*-value	Effect size (r)
SC1 vs. SC2	5.21 (1.51)	4.37 (1.26)	0.84	5.00	5.00	0.00	1.00	1.00	13	1	5	−3.087	.002	**−0.50**
SC1 vs. SC3	5.21 (1.51)	4.68 (1.25)	0.53	5.00	5.00	0.00	1.00	2.00	10	3	6	−1.539	.124 n.s.	**−0.25**
SC1 vs. SC4	5.21 (1.51)	2.90 (1.52)	2.31	5.00	3.00	2.00	1.00	2.00	17	2	0	−3.531	.000	**−0.57**
SC1 vs. SC5	5.21 (1.51)	5.74 (0.93)	−0.53	5.00	6.00	−1.00	1.00	1.00	6	8	5	−1.284	.199 n.s.	**−0.21**
SC2 vs. SC3	4.37 (1.26)	4.68 (1.25)	−0.31	5.00	5.00	0.00	1.00	2.00	5	8	6	−1.192	.233 n.s.	−0.19
SC2 vs. SC4	4.37 (1.26)	2.90 (1.52)	1.47	5.00	3.00	2.00	1.00	2.00	16	1	2	−3.130	.002	**−0.51**
SC2 vs. SC5	4.37 (1.26)	5.74 (0.93)	−1.37	5.00	6.00	−1.00	1.00	1.00	2	15	2	−3.209	.001	**−0.52**
SC3 vs. SC4	4.68 (1.25)	2.90 (1.52)	1.78	5.00	3.00	2.00	2.00	2.00	17	1	1	−3.572	.000	**−0.58**
SC3 vs. SC5	4.68 (1.25)	5.74 (0.93)	−1.06	5.00	6.00	−1.00	2.00	1.00	3	15	1	−2.689	.007 n.s.	**−0.44**
SC4 vs. SC5	2.90 (1.52)	5.74 (0.93)	−2.84	3.00	6.00	−3.00	2.00	1.00	1	17	1	−3.584	.000	**−0.58**

Adjusted *p* value = .005 (.05/10).
r< 0.20 = negligible; 0.20 ≤*r*< 0.50 = small; 0.50 ≤*r*< 0.80 = moderate; *r*≥ 0.80 = large
Shaded cells show the detection of statistically significant differences. Bold values show practically relevant effects.

Table 7. Results of the Wilcoxon signed-rank tests for the subjective assessment of gap's orientation difficulty (Q3).

Pairwise comparison	Mean 1 (SD)	Mean 2 (SD)	ΔMean	$M_{dn}1$	$M_{dn}2$	ΔM_{dn}	IQR1	IQR2	Positive	Negative	Ties	Test statistic	*p*-value	Effect size (r)
SC1 vs. SC2	5.00 (0.94)	5.20 (1.03)	−0.20	5.00	5.00	0.00	2.00	1.00	5	8	6	−1.00	.317 n.s.	−0.16
SC1 vs. SC3	5.00 (0.94)	4.79 (1.18)	0.21	5.00	5.00	0.00	2.00	1.00	11	6	2	−1.01	.315 n.s.	−0.16
SC1 vs. SC4	5.00 (0.94)	4.74 (1.33)	0.26	5.00	5.00	0.00	2.00	2.00	7	6	6	−0.90	.368 n.s.	−0.15
SC1 vs. SC5	5.00 (0.94)	5.42 (1.26)	−0.42	5.00	6.00	−1.00	2.00	1.00	2	8	9	−1.59	.112 n.s.	**−0.26**
SC2 vs. SC3	5.20 (1.03)	4.79 (1.18)	0.41	5.00	5.00	0.00	1.00	1.00	8	1	10	−2.31	.021 n.s.	**−0.38**
SC2 vs. SC4	5.20 (1.03)	4.74 (1.33)	0.46	5.00	5.00	0.00	1.00	2.00	9	2	8	−2.18	.029 n.s.	**−0.35**
SC2 vs. SC5	5.20 (1.03)	5.42 (1.26)	−0.22	5.00	6.00	−1.00	1.00	1.00	4	6	9	−1.03	.305 n.s.	−0.17
SC3 vs. SC4	4.79 (1.18)	4.74 (1.33)	0.05	5.00	5.00	0.00	1.00	2.00	6	6	7	−0.25	.805 n.s.	−0.04
SC3 vs. SC5	4.79 (1.18)	5.42 (1.26)	−0.63	5.00	6.00	−1.00	1.00	1.00	3	11	5	−2.24	.025 n.s.	**−0.36**
SC4 vs. SC5	4.74 (1.33)	5.42 (1.26)	−0.68	5.00	6.00	−1.00	2.00	1.00	1	10	8	−2.65	.008 n.s.	**−0.43**

Adjusted *p* value = .005 (.05/10).
r< 0.20 = negligible; 0.20 ≤*r*< 0.50 = small; 0.50 ≤*r*< 0.80 = moderate; *r*≥ 0.80 = large
Shaded cells show the detection of statistically significant differences. Bold values show practically relevant effects.

Table 8. Results of the Wilcoxon signed-rank test for the subjective assessment of glazing color appearance (Q13).

Pairwise comparison	Mean 1 (SD)	Mean 2 (SD)	ΔMean	$M_{dn}1$	$M_{dn}2$	ΔM_{dn}	IQR1	IQR2	Positive	Negative	Ties	Test statistic	*p*-value	Effect size (r)
SC1 vs. SC2	5.84 (1.21)	4.74 (1.45)	1.10	6.00	5.00	1.00	1.00	2.00	12	4	3	−2.25	.024 n.s.	**−0.37**
SC1 vs. SC3	5.84 (1.21)	5.11 (1.41)	0.73	6.00	5.00	1.00	1.00	1.00	10	3	6	−1.83	.067 n.s.	**−0.30**
SC1 vs. SC4	5.84 (1.21)	4.74 (1.52)	1.10	6.00	5.00	1.00	1.00	2.00	14	2	3	−2.57	.010 n.s.	**−0.42**
SC1 vs. SC5	5.84 (1.21)	6.21 (0.92)	−0.37	6.00	6.00	0.00	1.00	1.00	3	7	9	−1.31	.191 n.s.	**−0.21**
SC2 vs. SC3	4.74 (1.45)	5.11 (1.41)	−0.37	5.00	5.00	0.00	2.00	1.00	3	6	10	−1.15	.250 n.s.	−0.19
SC2 vs. SC4	4.74 (1.45)	4.74 (1.52)	0.00	5.00	5.00	0.00	2.00	2.00	6	6	7	0.00	1.000 n.s.	−0.05
SC2 vs. SC5	4.74 (1.45)	6.21 (0.92)	−1.47	5.00	6.00	−1.00	2.00	1.00	2	15	2	−3.21	.001	**−0.52**
SC3 vs. SC4	5.11 (1.41)	4.74 (1.52)	0.37	5.00	5.00	0.00	1.00	2.00	8	4	7	−1.12	.262 n.s.	−0.18
SC3 vs. SC5	5.11 (1.41)	6.21 (0.92)	−1.10	5.00	6.00	−1.00	1.00	1.00	2	12	5	−2.49	.013 n.s.	**−0.40**
SC4 vs. SC5	4.74 (1.52)	6.21 (0.92)	−1.47	5.00	6.00	−1.00	2.00	1.00	1	14	4	−3.00	.003	**−0.49**

Adjusted *p* value = .005 (.05/10).
r< 0.20 = negligible; 0.20 ≤*r*< 0.50 = small; 0.50 ≤*r*< 0.80 = moderate; *r*≥ 0.80 = large
Shaded cells show the detection of statistically significant differences. Bold values show practically relevant effects.

after a different previous state: SC2 was always set after the EC façade had been in its fully bleached state, and SC3 after the fully tinted. Other than emphasizing different times that the EC glazing would need to complete their switch and reach the set visual transmission after a previous setting, this also shows that a "memory" effect could bias subjective evaluations, with participants being more likely to give higher rating of acceptance and satisfaction after they had experienced the lighting environment with the façade in its deep blue fully colored state. This emphasizes the importance of further investigation on the influences of dynamic changes in illuminance and CCT under dynamic control of EC glazing in terms of visual and luminous experience, while also considering effects of the light beyond vision (e.g., opportunities for circadian entrainment) (Kompier et al. 2021).

With respect to the user-controlled scenario (SC5), the results suggest that, when the participants were given control of the EC façade to their preferred setting, their assessment was better compared to the mixed (SC2 and SC3) and fully tinted (SC4) glazing settings. This finding corroborates evidence from previous research, in all domains of indoor environmental quality, reinforcing the relevance of individual control in personal assessments (Day et al. 2019). Interestingly, across all comparisons made between subjective evaluations, no significant differences could be detected in participants' perception, acceptance, and satisfaction of the internal and external luminous environment between the bleached state of the façade (SC1) and the user-controlled scenario (SC5). This, regardless of the fact that illuminance and luminance levels, as well as color temperature and color rendering of the light, was substantially different between these two scenarios (Tables 1 and 3). In this context, a study by Lee et al. (2012) showed a pattern of overriding automated EC glazing designed to control solar gains, daylight, and discomfort glare by manual switching, which may be linked to user satisfaction. This suggests that, when given control, subjects' preferences and satisfaction of their luminous conditions can be independent of the actual physical environment, in agreement also with relevant literature (Galasiu and Veitch 2006).

Lastly, in terms of glare perception, across the five EC scenarios, the analysis of the data did not detect statistically significant differences in participants' responses related to discomfort due to glare from the façade. However, despite of the test conditions being under a predominantly overcast sky, and the mean and median calculated daylight glare probability being always DGP ≤ 0.25, perceptible and disturbing glare was reported for, respectively, 31% and 5% of the experimental sessions (Fig. 9). Reports of disturbing glare were collected specifically under the bleached (SC1) and user-controlled (SC5) scenarios, which could be due to higher vertical illuminance under these conditions (Table 1). Interestingly, perceptible glare was also reported under the mixed and fully tinted settings (Fig. 9), possibly suggesting that there might be other factors influencing glare perception than the conventional photometric and physical variables featured in glare formulae, including potential higher sensitivity to light spectra characterized by shorter wavelengths (Flannagan et al. 1989; Jain et al. 2023; Yang et al. 2018) or, potentially, the presence of a range effect (Kent and Jakubiec 2021). This, however, needs more comprehensive investigation to address possible links between the tinted daylight filtered through chromatic glazing and the subjective evaluation of glare sensation.

5. Conclusions

In this experimental study, we investigated the impact of the spectral composition of daylight filtered through EC glazing on visual task performance and visual perception. Nineteen participants were exposed to five setting scenarios of a 6-pane EC façade (fully bleached, mixed setting after fully bleached, fully tinted, mixed setting after fully tinted, and user-controlled) in a west-facing test room under predominantly overcast sky conditions. Subjects were asked to perform a chromatic Landolt rings task and evaluate their internal and external luminous environment under each EC glazing condition. The following conclusions can be drawn from the analysis of data:

- Dynamic changes in the spectral composition of daylight through different states of the EC façade did not have a statistical and practically relevant influence on visual task performance in terms of visual acuity and color naming accuracy, nor on participants' subjective evaluation of the tasks' difficulty.
- Daylight filtered through the fully tinted EC glazing ($\tau v = 2\%$) substantively impacted participants' acceptance and satisfaction, resulting in lower ratings for perception of daylight availability and satisfaction with color appearance of the indoor and outdoor luminous environment. Subjective evaluations were supported by the measurements of light spectra showing a pronounced shift in the SPD curve toward the blue part, and lower levels of luminous parameters.
- The mixed EC scenarios used in this study had better satisfaction and acceptance ratings of the color appearance of the indoor environment and of the outside view with respect to a fully tinted state, without excessively compromising daylight availability.
- As evidenced in previous studies (Mardaljevic et al. 2014; Mardaljevic et al. 2016), a mixed glazing setting of an EC façade, with panes in their bleached (bottom) and tinted (top) state, can improve the feeling of "naturality" of the incoming daylight, with only a slight change in its spectral power distribution. The resulting color temperature was measured to be lower than the bleached setting due to differences in the contribution of diffuse light from the sky component and of the light reflected off the surrounding landscape.
- When comparisons were made between the ratings given by participants under the bleached and tinted states and under the mixed scenarios, the reported evaluations differed depending on the previous setting. This leads to postulate a potential activation and memory effect on user perception due to

dynamic daylight transitions through an EC façade.

- Participants' subjective evaluations of the internal and external color appearance was consistently higher when they were given control of the EC façade setting with respect to the mixed and fully tinted scenarios. No significant and practically relevant differences could be detected when the user-controlled scenario was compared to the fully bleached state, although the former setting resulted in generally lower lighting levels and higher CCT. This result might be relevant to increase user acceptance of a dynamically switchable façade, while providing the levels of luminous and solar protection required (and offering activation potential that goes beyond the sole consideration of visual effects).
- Although the experiment described in this study was not specifically designed to explore participants' responses to discomfort due to glare, the results lead to postulate that there might be other factors influencing glare perception than the customary photometric and physical variables featured in glare formulae, including consideration of potential higher sensitivity to shorter wavelengths lighting spectra.

Before these results can be generalized, and transferred to the lighting and façade industry, some methodological and experimental limitations should be acknowledged. In first instance, this study solely focused on user perception of daylight filtered through an EC façade while avoiding extreme luminous conditions that might engender drastic or significant changes in the distribution and CCT of daylight (Condit and Grum 1964) or severe glare occurrence (Jain et al. 2021, 2022). The outcomes of this study are also only relevant to blue-tinted EC glazing. The spectral composition of daylight through other colors of a switchable façade technology may lead to different effects on visual perception and task performance (Chen et al. 2019; Liang et al. 2021). In this study, only a particular configuration for a mixed setting of the EC façade was tested (the upper part being fully tinted, and the lower fully bleached). Other combinations of glazing settings, both in terms of visible transmittance of the EC panes and their arrangement, may lead to different outcomes. Lastly, based on prior research (Smolders and De Kort 2017), it is expected that subjective responses to the luminous environment may be dependent on time of day (Kent et al. 2017), which was not investigated in this study due to the limited availability of the test room and the procedural constraint in running a repeated-measures experimental design. Together with the comprehensive characterization of subjective assessments and glare evaluations of an EC façade with the sun in the direct field of view (Clear et al. 2006; Jain et al. 2021, 2022), and consideration of the potential combination of visual and non-visual effects resulting from the control strategies of the EC glazing, these all represent very promising avenues for future research.

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References

Ajaji Y, André P. 2015. Thermal comfort and visual comfort in an office building equipped with smart electrochromic glazing: an experimental study. Energy Procedia. 78:2464–2469. doi: 10.1016/j.egypro.2015.11.230.

Allen IE, Seaman CA. 2007. Likert scales and data analyses. Qual Prog. 40:64–65.

Arsenault H, Hébert M, Dubois MC. 2012. Effects of glazing colour type on perception of daylight quality, arousal, and switch-on patterns of electric light in office rooms. Build Environ. 56:223–231. doi: 10.1016/j.buildenv.2012.02.032.

Boyce P, Akashi Y, Hunter C, Bullough J. 2003. The impact of spectral power distribution on the performance of an

achromatic visual task. Lighting Res Technol. 35 (2):141–156.
Boyce P, Eklund N, Mangum S, Saalfield C, Tang L. 1995. Minimum acceptable transmittance of glazing. Light Res Technol. 27(3):145–152.
Cabin RJ, Mitchell RJ. 2000. To Bonferroni or not to Bonferroni: when and how are the questions. Bull Ecol Soc Am. 81:246–248. doi: 10.2307/20168454.
Cauwerts C, Jost S, Deroisy B. 2019. Colorimetric accuracy of high dynamic range images for lighting research. 29th Quadrennial Session of the CIE-CIE 2019 Connecting the World in Light. doi: 10.25039/x46.2019.OP89.
CEN European Daylight Standard. 2019. EN17037: 2019 daylight in buildings.
Chen X, Zhang X, Du J. 2019. Glazing type (colour and transmittance), daylighting, and human performances at a workspace: a full-scale experiment in Beijing. Build Environ. 153:168–185. doi: 10.1016/j.buildenv.2019.02.034.
Ciampi G, Scorpio M, Spanodimitriou Y, Rosato A, Sibilio S. 2020. Thermal model validation of an electric-driven smart window through experimental data and evaluation of the impact on a case study. Build Environ. 181:107134. doi: 10.1016/j.buildenv.2020.107134.
Clear R, Inkarojrit V, Lee E. 2006. Subject responses to electrochromic windows. Energ Buildings. 38(7):758–779.
Condit H, Grum F. 1964. Spectral energy distribution of daylight. JOSA. 54:937–944. doi: 10.1364/JOSA.54.000937.
Consilium Ophthalmologicum Universale. 1984. Visual acuity measurement standard. Visual Functions Committee.
Day JK, Futrell B, Cox R, Ruiz SN, Amirazar A, Zarrabi AH, Azarbayjani M. 2019. Blinded by the light: occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies. Build Environ. 154:107–121. doi: 10.1016/j.buildenv.2019.02.037.
De Kort YA. 2019. Tutorial: theoretical considerations when planning research on human factors in lighting. Leukos. 15 (2–3):85–96.
Ellis PD. 2010. The essential guide to effect sizes: statistical power, meta-analysis, and the interpretation of research results. Cambridge (UK): Cambridge University Press. doi: 10.1017/CBO9780511761676.
Ferguson CJ. 2009. An effect size primer: a guide for clinicians and researchers. Prof Psychol Res Pract. 40(5):532. doi: 10.1037/a0015808.
Field A. 2013. Discovering statistics using IBM SPSS statistics. London: Sage.
Field A, Hole G 2002. How to design and report experiments. Sage.
Flannagan MJ, Sivak M, Ensing M, Simmons CJ 1989. Effect of wavelength on discomfort glare from monochromatic sources. Ann Arbor: University of Michigan, Transportation Research Institute. Report No: uMTRI-89-30. [accessed 2023 July 22]. https://deepblue.lib.umich.edu/bitstream/handle/2027.42/64064/78939.pdf?sequence=1&isAllowed=y.
Fotios S, Cheal C. 2007. Lighting for subsidiary streets: investigation of lamps of different SPD. Part 1—visual performance. Light Res Technol. 39(3):215–232.
Galasiu AD, Veitch JA. 2006. Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. Energ Build. 38(7):728–742.
Górnicka G. 2008. Lighting at work: environmental study of direct effects of lighting level and spectrum on psychophysiological variables [thesis]. Technische Universiteit Eindhoven. doi: 10.6100/IR639378.
Houser KW, Esposito T, Royer MP, Christoffersen J. 2022. A method and tool to determine the colorimetric and photobiological properties of light transmitted through glass and other optical materials. Build Environ. 215:108957. doi: 10.1016/j.buildenv.2022.108957.
Hubai Z. 2014. qDslrdashboard. [accessed 2023 July 22]. https://dslrdashboard.info/.
Inanici MN. 2006. Evaluation of high dynamic range photography as a luminance data acquisition system. Light Res Technol. 38(2):123–134.
Jain S, Karmann C, Wienold J. 2021. Subjective assessment of visual comfort in a daylit workplace with an electrochromic glazed façade. J Phys Conf Ser. 2042:012179.
Jain S, Karmann C, Wienold J. 2022. Behind electrochromic glazing: assessing user's perception of glare from the sun in a controlled environment. Energ Buildings. 256:111738. doi: 10.1016/j.enbuild.2021.111738.
Jain S, Wienold J. 2021. Glare behind blue (electrochromic) glazing. In: 19th Annual International Radiance Workshop. Bilbao (Spain).
Jain S, Wienold J, Lagier M, Schueler A, Andersen M. 2023. Perceived glare from the sun behind tinted glazing: comparing blue vs. color-neutral tints. Build Environ. 234:110146. doi: 10.1016/j.buildenv.2023.110146.
Jakubiec JA, Van Den Wymelenberg K, Inanici M, Mahic A. 2016a. Accurate measurement of daylit interior scenes using high dynamic range photography. In: Proceedings of the CIE 2016 Lighting Quality and Energy Efficiency Conference. Melbourne (Australia).
Jakubiec JA, Van Den Wymelenberg K, Inanici M, Mahic A. 2016b. Improving the accuracy of measurements in daylit interior scenes using high dynamic range photography. In: Proceedings of the 32nd PLEA Conference. Los Angeles (CA). p. 11–13.
Kent MG, Altomonte S, Tregenza P, Wilson R. 2016. Temporal variables and personal factors in glare sensation. Lighting Res Technol. 48(6):689–710.
Kent MG, Altomonte S, Wilson R, Tregenza PR. 2017. Temporal effects on glare response from daylight. Build Environ. 113:49–64. doi: 10.1016/j.buildenv.2016.09.002.
Kent MG, Jakubiec JA. 2021. An examination of range effects when evaluating discomfort due to glare in Singaporean buildings. Light Res Technol. 54(6):514–528. doi: 10.1177/14771535211047220.
King AP, Eckersley R. 2019. Inferential statistics III: nonparametric hypothesis testing. Stat Biomed Eng Sci. 119–145. doi: 10.1016/B978-0-08-102939-8.00015-3.
Ko WH, Kent MG, Schiavon S, Levitt B, Betti G. 2022. A window view quality assessment framework. Leukos. 18(3):268–293. doi: 10.1080/15502724.2021.1965889.

Kompier ME, Smolders KC, De Kort YA, Steinborn MB. 2021. Abrupt light transitions in illuminance and correlated colour temperature result in different temporal dynamics and interindividual variability for sensation, comfort and alertness. PLOS ONE. 16(3):e0243259.

Kompier ME, Smolders KC, Marken Lichtenbelt WV, De Kort YA. 2020. Effects of light transitions on measures of alertness, arousal and comfort. Physiol Behav. 223:112999. doi: 10.1016/j.physbeh.2020.112999.

Lampert CM. 1998. Smart switchable glazing for solar energy and daylight control. Sol Energy Mater Sol Cells. 52(3–4):207–221.

Lee ES, Claybaugh ES, Lafrance M. 2012. End user impacts of automated electrochromic windows in a pilot retrofit application. Energ Buildings. 47:267–284. doi:.10.1016/j.enbuild.2011.12.003.

Lee ES, Dibartolomeo D. 2002. Application issues for large-area electrochromic windows in commercial buildings. Sol Energy Mater Sol Cells. 71:465–491. doi: 10.1016/S0927-0248(01)00101-5.

Liang R, Kent M, Wilson R, Wu Y. 2019. Development of experimental methods for quantifying the human response to chromatic glazing. Build Environ. 147:199–210. doi: 10.1016/j.buildenv.2018.09.044.

Liang R, Kent M, Wilson R, Wu Y. 2021. The effect of thermochromic windows on visual performance and sustained attention. Energ Buildings. 236:110778. doi: 10.1016/j.enbuild.2021.110778.

Logadóttir Á, Fotios SA, 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 Res Appl. 38(1):46–57.

Mardaljevic J, Andersen M, Roy N, Christoffersen J. 2014. A framework for predicting the non-visual effects of daylight–part II: the simulation model. Lighting Res Technol. 46(4):388–406.

Mardaljevic J, Kelly Waskett R, Painter B. 2014. Electrochromic glazing: avoiding the blues. In: CIBSE ASHRAE Technical Symposium. Dublin (Ireland).

Mardaljevic J, Kelly Waskett R, Painter B. 2016. Neutral daylight illumination with variable transmission glass: theory and validation. Lighting Res Technol. 48(3):267–285.

Maxwell SE, Delaney HD. 2004. Designing experiments and analyzing data: a model comparison perspective. New York: Psychology Press.

Moeck M, Lee E, Rubin M, Sullivan R, Selkowitz S. 1996. Visual quality assessment of electrochromic and conventional glazings. CA (USA): Lawrence Berkeley National Lab.

Osterhaus WK, Bailey IL. 1992. Large area glare sources and their effect on discomfort and visual performance at computer workstations. In: Conference Record of the 1992 IEEE Industry Applications Society Annual Meeting. Houston (TX). doi: 10.1109/IAS.1992.244537.

Pereira DG, Afonso A, Medeiros FM. 2015. Overview of Friedman's test and post-hoc analysis. Commun Stat Simul Comput. 44:2636–2653. doi: 10.1080/03610918.2014.931971.

Piccolo A, Pennisi A, Simone F. 2009. Daylighting performance of an electrochromic window in a small scale test-cell. Sol Energy. 83(6):832–844.

Piccolo A, Simone F. 2009. Effect of switchable glazing on discomfort glare from windows. Build Environ. 44(6):1171–1180.

Pierson C, Cauwerts C, Bodart M, Wienold J. 2021. Tutorial: luminance maps for daylighting studies from high dynamic range photography. Leukos. 17(2):140–169.

Pierson C, Wienold J, Bodart M. 2018. Review of factors influencing discomfort glare perception from daylight. Leukos. 14(3):111–148.

Rubin M, Lee E, Sullivan R, Finlayson E, Hopkins D. 1994. A review of electrochromic window performance factors. In: SPIE 13. International Symposium on Optical Materials Technology for Energy Efficiency and Solar Energy Conversion. Freiberg (Germany).

Sawilowsky S, Salkind N. 2007. Mann-Whitney U test (Wilcoxon rank-sum test). Encycl Meas Stat. 2:565–567.

Scorpio M, Ciampi G, Rosato A, Maffei L, Masullo M, Almeida M, Sibilio S. 2020. Electric-driven windows for historical buildings retrofit: energy and visual sensitivity analysis for different control logics. J Build Eng. 31:101398. doi: 10.1016/j.jobe.2020.101398.

Shamsul B, Sia C, Ng Y, Karmegan K. 2013. Effects of light's colour temperatures on visual comfort level, task performances, and alertness among students. Am J Public Health Res. 1(7):159–165.

Smolders KC, De Kort YA. 2017. Investigating daytime effects of correlated colour temperature on experiences, performance, and arousal. J Environ Psychol. 50:80–93. doi: 10.1016/j.jenvp.2017.02.001.

Smolders K, De Kort YA, Cluitmans P. 2012. A higher illuminance induces alertness even during office hours: findings on subjective measures, task performance and heart rate measures. Physiol Behav. 107(1):7–16.

Suk JY. 2014. Absolute glare and relative glare factors: predicting and quantifying levels of interior glare and exterior glare caused by sunlight and daylight [thesis]. University of Southern California.

Ward GJ. 2005. Photosphere. http://www.anyhere.com/.

Wienold J, Andersen M. 2016. Evalglare 2.0–new features faster and more robust hdr-image evaluation. 15th International Radiance Workshop; Padova, Italy.

Wilcoxon F. 1992. Individual comparisons by ranking methods. Breakthroughs in statistics. New York: Springer.

Wilkins AJ, Evans BJW, Plant GT. 2022. Potential uses for precision tinted lenses in a neurology clinic. US Neurol. 18(2):93–102. doi: 10.17925/USN.2022.18.2.93.

Yang Y, Luo RM, Huang W. 2018. Assessing glare, part 3: glare sources having different colours. Lighting Res Technol. 50(4):596–615.

Zinzi M. 2006. Office worker preferences of electrochromic windows: a pilot study. Build Environ. 41(9):1262–1273.