Energy & Buildings 256 (2022) 111738

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Behind electrochromic glazing: Assessing user's perception of glare from the sun in a controlled environment

Sneha Jain *, Caroline Karmann, Jan Wienold

Laboratory of Integrated Performance in Design (LIPID), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne 1015, Switzerland

ARTICLE INFO

Article history:
Received 1 July 2021
Revised 2 November 2021
Accepted 25 November 2021
Available online 29 November 2021

Keywords:
Discomfort glare
Electrochromic glazing
User assessment
Daylight

ABSTRACT

The adaptable transmittance of electrochromic glazing allows to control the solar radiation entering buildings, yet the level of transmittance needed to protect from glare is still an unanswered question. To bridge this gap, this study evaluates the level of visible light transmittance (τ_v) required for blue-tinted low transmittance glazing to prevent discomfort glare when the sun is visible through the glazing. Twenty participants were exposed to four visual scenarios with varying viewing directions and window transmittance. Results indicate that when the sun is close to the central field of view, a normal-hemispherical transmittance, $\tau_{v,\ n\text{-}h}$ of 0.6% prevents disturbing glare for most users but does not provide a comfortable situation (this condition corresponds to a "seen" sun disc's luminance of 4.8 M cd/m^2). To achieve comfortable situations, a $\tau_{v,\ n\text{-}h}$ of 0.14% was found suitable. For non-critical viewing directions, $\tau_{v\ n\text{-}h}$ of 0.6% is sufficient to achieve visually comfortable space for most participants. This study also examined the reliability of five discomfort glare metrics by comparing their objective output to subjective responses for the tested conditions. The contrast-based metrics (Daylight Glare Probability, CIE Glare Index, Unified Glare Probability, Daylight Glare Index) possess a valid positional sensitivity and show higher Spearman's rank correlations (ρ – 0.56–0.59) compared to solely saturation-based metrics as the vertical illuminance (E_v) (ρ – 0.44).

1. Introduction

A considerable number of studies published in recent years have proven the benefits of daylight and view out in indoor spaces for the building occupants [1,2]. Windows in workplace environment providing access to sunlight and outside view have been associated with alleviated stress at work [3] and improved productivity [4]. Research in this area have greatly impacted standards and guidelines in defining the recommendations for daylight availability, visual comfort and view out [5,6]. Windows and shading devices play a key role in allowing sufficient daylight into the building and providing a view to the outside. An increasing number of commercial buildings are utilizing glass as the main facade element to have a larger window to wall ratio for facilitating a view to the outdoors and access to daylight. However, larger windows with an increased amount of daylight penetration are also responsible for excessive brightness, intense reflections, and strong contrast, which are all causes of glare from daylight [7]. Electrochromic glazing (EC) has a big potential market in such settings with large glass façade for their ability to modulate daylight in the buildings in addition to their energy-saving capabilities [8]. The electrochromic glazing system consists of multilayer coatings on the glass which on applying low voltage induces ion migration from the EC layer resulting in modulation of the optical properties seen as a colour change of the glazing. This modulation is reversible therefore allowing dynamic control of solar heat and daylight entering the building. This article focuses on evaluating the switchable visible transmittance of EC glazing for minimizing the perceived discomfort glare from the sun in the human visual field.

Discomfort glare causes visual irritation or annoyance without necessarily impairing the vision [9]. Discomfort glare can be caused by excessive brightness i.e., the saturation effect or by extreme differences in bright and dark areas i.e., the contrast effect. Glare indices, including the Daylight Glare Index (DGI) [10], the Predicted Glare Sensation Vote (PGSV) [11], the Unified Glare Rating (UGR) [12], the CIE Glare Index (CGI) [13] and the Daylight Glare Probability (DGP) [14], typically quantify glare by examining

Abbreviations: EC, Electrochromic; τ_v, Visible light transmittance; $\tau_{v\ n\text{-}h}$, Normal-hemispherical visible light transmittance; DGP, Daylight Glare Probability; UGP, Unified Glare Probability; DGI, Daylight Glare Index; CGI, CIE Glare Index; E_v, Vertical illuminance at eye; FOV, Field of View.

* Corresponding author.
E-mail address: Sneha.jain@epfl.ch (S. Jain).

https://doi.org/10.1016/j.enbuild.2021.111738
0378-7788/

the human field of vision. Further, glare metrics can be divided into 3 categories [15]: Metrics dominated by the contrast effect (DGI, UGR and CGI fall in that category), metrics solely based on the saturation effect (e.g., vertical illuminance E_v or average luminance) and hybrid metrics (DGP, PGSV), based on both effects. Metrics using the contrast effect in their equation are based on luminance, position, and size of the glare source in relation to the adaptation level (background luminance L_b or vertical illuminance E_v), as described in the general equation (1).

$$Discomfort\ Glare = f(L_s, \omega)\ / f(L_b, P) \tag{1}$$

where L_s is the luminance of glare source (cd/m^2), omega is the solid angle of source, L_b is the background luminance (cd/m^2) and P is the position index. Note: DGP uses E_v as adaptation level instead of L_b.

Metrics relying on the saturation effect use the amount of light at eye level as the basis (typically E_v or L_{avg}). DGPs (simplified DGP [16]) is an often-used metric of this category [17–19]. Hybrid metrics combine the two effects in their equation (e.g. DGP, PGSV). DGP has been shown to be a robust and widely reliable metric in several studies[15,20] and has been adopted as glare metric in the European standard ‘‘daylight in buildings" EN17037 [6].

1.1. State of the art

Addressing the discomfort from daylight glare is all the more crucial as it is a common source of disturbance for building occupants [21], which can affect one's perceived level of productivity [22]. Electrochromic (EC) glazing is a technology that can modulate the incoming daylight into the building by utilizing their ‘‘switchable" transmittance technology while maintaining a clear view to the outside environment. We found in the literature many studies evaluating this technology. The studies were sometimes purely based on estimations (simulations) and physical measurements or based on people (human subject testing and field studies).

Early simulation work from Moeck et al. showed the evaluation of the visual comfort of EC glazing, their ability to provide a more constant glare-free daytime environment compared to their static counterparts [23]. Lee and DiBartolomeo conducted in-situ measurements on a large-area EC window of τ_v between 11% and 38% [24]. The borderline discomfort glare scenarios were categorized based on calculated vertical illuminance. It was found to oftentimes reach 'just intolerable' during the monitoring period. The authors further estimated that transmittances of less than 1% are needed to reduce luminance to comfortable levels. Lee et al. later conducted another experimental study to evaluate the performance of EC window prototypes, using a full-scale office test-bed during the equinox period [25]. The authors were able to show the benefits of EC glazing in terms of lighting energy savings (59 % in comparison with static windows) but did not tackle the issue of glare. Piccolo and Simone demonstrated, through an experimental study based on physical measurements in a scaled test-cell equipped with EC glazing, its effectiveness in reducing glare from bright light at high sun angles while allowing daylight penetration. However, they did not test its effectiveness at low sun angles which would entail very low transmittance states [26]. Using a similar setting, the same group noted that their switchable glazing (minimum τ_v of 6.8%) could fully address glare from direct sun [27]. Ajaji and André conducted laboratory experiments based on physical measurements to assess the performance of EC glazing on visual and thermal comfort. They concluded that EC glazing can solve the problems of overheating and over-illumination while maintaining good daylight autonomy, but may not address discomfort due to glare [28].

In addition to studies based on simulation and physical measurements in laboratory conditions, we also found user assessment studies evaluating glare when using EC-glazing. Clear et al. conducted a laboratory study on 43 participants working in an office-like room with manually switchable EC windows, manually operated venetian blinds, and dimmable fluorescent lights with the sun in the peripheral zone of the field of view (FOV) [29]. Clear and al. showed that the EC windows reduced the incidence of glare compared to working under a fixed transmittance (60%) condition, with 50% of the subjects setting the window transmittance at 3% (lowest level available). Zinzi conducted a pilot study in an office-like room with a manually switchable EC, where the sun was not in the FOV of participants [30]. Thirty employees of the research facility participated in the study. The lowest visual transmittance reached by the glazing was 14.4%, which led to 16.7% of glare reports. The author concluded that it is possible to obtain uniform conditions when no direct sun or high sky illuminance is in the user's FOV. Page et al. assessed the performance of EC glazing with a minimum τ_v of 15 %, coupled to an anidolic daylighting system installed in an office via physical measurements, occupant survey and simulations [31]. The EC glazing showed good overall performance, but the authors noted that it was not able to eliminate all sources of glare, even in its state of minimal transmission for clear sky situations. Lee et al. conducted field measurements to investigate occupant interaction with EC glazing in a building [32]. The authors found that systematic subjective data collection was not possible, as the occupants of the study spaces changed, and space was not occupied at regular intervals. The authors hypothesized that occupants were likely to use the tint level of the lower EC windows to warrant non-use of the blinds and allow a view out in case of discomfort glare. Kelly et al. reported on the retrofit application of EC glazing (minimum τ_v 2%) in a typical office building. The authors noted that around the winter solstice period, an occupant who is seated facing the window reported visual discomfort on sunny days when the solar disc was directly in the FOV [33,34]. Day and al. conducted field measurements and surveys of three large office buildings, one of which utilized EC glazing with a minimum τ_v of 1%. EC was implemented as a retrofit solution [22]. EC glazing control was automated (no occupant override and no compensation for daylight reduction) and based on both the presence of direct sunlight on the façade and direct sunlight penetration into the building. The EC glass would tint to 1% when direct sunlight penetrates more than three feet into the building. Survey results indicated a low occurrence of glare on the screen, but nothing was reported about discomfort glare from direct sun in the FOV. The authors noted that the superior glare control by EC glass deeply affected the overall illumination and the subsequent overall satisfaction of the occupants.

This review showed us that up to now there is no clear knowledge on the maximum acceptable τ_v of EC glazing to effectively address glare from direct sun in one's FOV. Further, none of these studies evaluated the performance of discomfort glare metrics (nor its related threshold) in comparison to the people's subjective assessment conducted in the EC glazing setup.

1.2. Objectives

The goals of this study are to evaluate: (1) the performance of EC glazing in minimizing discomfort glare in a controlled user assessment setup, and (2) the performance of five discomfort glare metrics (DGP, CGI, UGP, E_v and DGI) in predicting perceived human discomfort due to glare in scenarios with the sun in the FOV through EC glazing. From the subjective assessments, we also determine the transmittance level of the glazing needed to ensure visual comfort.

To address these objectives, we conducted an experimental study with 20 participants in a semi-controlled office-like setup where participants experienced the pre-defined daylit visual scenarios and provided their subjective evaluations. The method and results of the study are detailed in the subsequent sections.

2. Method

This study follows a psychophysical approach where the relationship between the subjective responses and the physical stimuli (daylight glare from the sun in the FOV) is investigated through laboratory tests in a semi-controlled environment. Four physical stimuli (also referred as scenarios), varying in glare source luminance and viewing direction, were presented to each subject. The luminance of the glare source (sun) was varied within the subjects by changing the transmittance of EC glazing. Daylight was the only source of light.

2.1. Study design

The study is a single-blind, within-subject design (repeated measurements), where every subject experience four visual scenarios in random order. The dependent variable is the discomfort glare perception, and the independent variables are the luminance of the glare source and the viewing direction in relation to the glare source. A within-subjects design was selected as it requires fewer participants and offers an increase in statistical power [35].

The desired sample size was derived from a power calculation in Gpower calculator tool 3.1.9.4 [36] assuming repeated measurements, within factors ANOVA test considering one group and four measurements, assuming an effect size of 0.30, alpha 0.05 and a power of 0.95. This calculation resulted in a sample size of 24 participants. However, due to the restrictions from the Covid-19 situation, only 20 participants could be tested before the lockdown of March 2020.

Twenty university students (min = 19 years, max = 30 years, median = 23 years) participated in our study. Our sample included 15 males and 5 females. The requirements for selection were to be in healthy conditions, have a normal colour vision, no other visual impairment such as cataract, age group between 18 and 30 years, have a BMI between normal ranges, must have English proficiency level C1 or higher, must not use drugs and must not abuse of alcohol. Besides these criteria, volunteers that knew the researchers' topic and the laboratory or that studied disciplines related to the investigated field (i.e., architecture and civil engineering) were excluded from the study to avoid response bias. Individuals participating were compensated as per the local regulations. The protocol, further detailed below, was approved by the Human Research Ethics Committee at EPFL (ref. No. HREC 035-2019).

2.2. Test room set-up and equipment

The experiments were conducted in a test room located on the EPFL campus in Lausanne, Switzerland (46°31′00.4″N 6°33′47.1″E). The test room is 6.55 m deep, 3.05 m wide and 2.65 m high and allowed direct contact with the outside environment (Fig. 1). The test room has north and south facing window facades with a window-to-wall ratio of 62%. Both the facades have a white blackout curtain installed which can be drawn to block the daylight entering the room when needed. For these experiments, the north facade was completely closed by the blackout curtain (white color towards the inside). The south facade was equipped with six EC glazed window units and was used as a testing facade (Fig. 1(a and b)). The transmittance of each pane could be individually controlled by an added control system interface. This control system also provided feedback when the glazing was completely switched. The measured $\tau_{v,\ n\text{-}h}$ values ranged between 56% (bleached) and 0.6% (fully tinted). The test room was furnished with two office desks, one for the participant and one for the researcher conducting the experiments. The participant's desk was placed close to the south facade with a view directed towards the window, and the researcher's desk was placed close to the north facade on the other end of the room, looking over the participant's desk as shown in the layout (Fig. 1(c)). The researcher's computer was used to control and monitor this equipment used in the experiment including the control of EC glazing by using the custom-made tool. The participant's desk was equipped with a computer used to perform certain tasks and answer an online questionnaire during the experiment.

The test room was equipped with instruments for recording visual and thermal parameters of the indoor environment in the room. A layout of the test room with the location of all equipment is shown in Fig. 1(c). The participant's desk was equipped with four *Hagner Special Detector SD2* to measure continuously the illuminance at 10 s interval and the associated Multi-Channel Amplifier (model MCA-1600) was mounted below the desk out of the sight of the participant. Two of these sensors were installed on the desk to measure the horizontal illuminance at the left and right of the participant's desk. The other two sensors were installed at the front and at the back of the participant's computer screen to measure the vertical illuminance in both directions. A calibrated luminance camera *LMK 98-4 color HighRes* camera with a fish-eye lens (type Dörr Digital Professional DHG, equidistant projection) and a neutral density filter ND3 were used to capture the High Dynamic Range (HDR) images of each visual scene at participant's eye position before and after their exposure. The images were captured using the software Labsoft available for the LMK camera. A handheld LMT illuminance sensor was mounted just below the lens of the LMK camera to record the respective vertical illuminance value for each captured image at the participant's eye level. An *OceanOptics* spectroradiometer was mounted at the back of the subject's computer screen facing the window to measure the spectrum of the incoming daylight through the window. A temperature, humidity, and airflow meter *Testo 480* with its probes was used to continuously record the air and globe temperature, air velocity, relative humidity, and CO_2 content in the test room. The test room was also equipped with dimmable electric lights, but they were only used during the pre- and post-phases of the experimental session.

2.3. Transmittance of EC glazing panes

The visual scenarios were created by altering the EC glazing transmittance levels using a network interface. For this study, we tested three different transmittance levels for the window, where the sun can be seen ("sun window") as shown in Fig. 2:

1. The lowest switching state (nominal $\tau_{v,\ n\text{-}h}$ = 0.9% according to the manufacturer)
2. A switching state slightly higher than 1) (nominal $\tau_{v,\ n\text{-}h}$ = 2% according to the manufacturer)
3. One level even below the normal range of EC glazing by installing an additional removable filter of $\tau_{v,\ n\text{-}h}$ = 22% transmittance on the window switched to the lowest possible stage (nominal $\tau_{v,\ n\text{-}h}$ =22%)

In addition to this, we also measured the transmittance in fully-bleached state (nominal $\tau_{v,\ n\text{-}h}$ = 59%) and an intermediate state (nominal $\tau_{v,\ n\text{-}h}$ = 5.5%) that we used for rest of the view windows as shown in Fig. 2.

For two of the six glazing units the spectral transmittance was measured in a glazing and nano-technology laboratory on its window test bench after conducting the user assessments. The measurement procedure and setup are described by Steiner et. al [37] and measurement uncertainty of a $\tau_{v,\ n\text{-}h}$ measurement is less

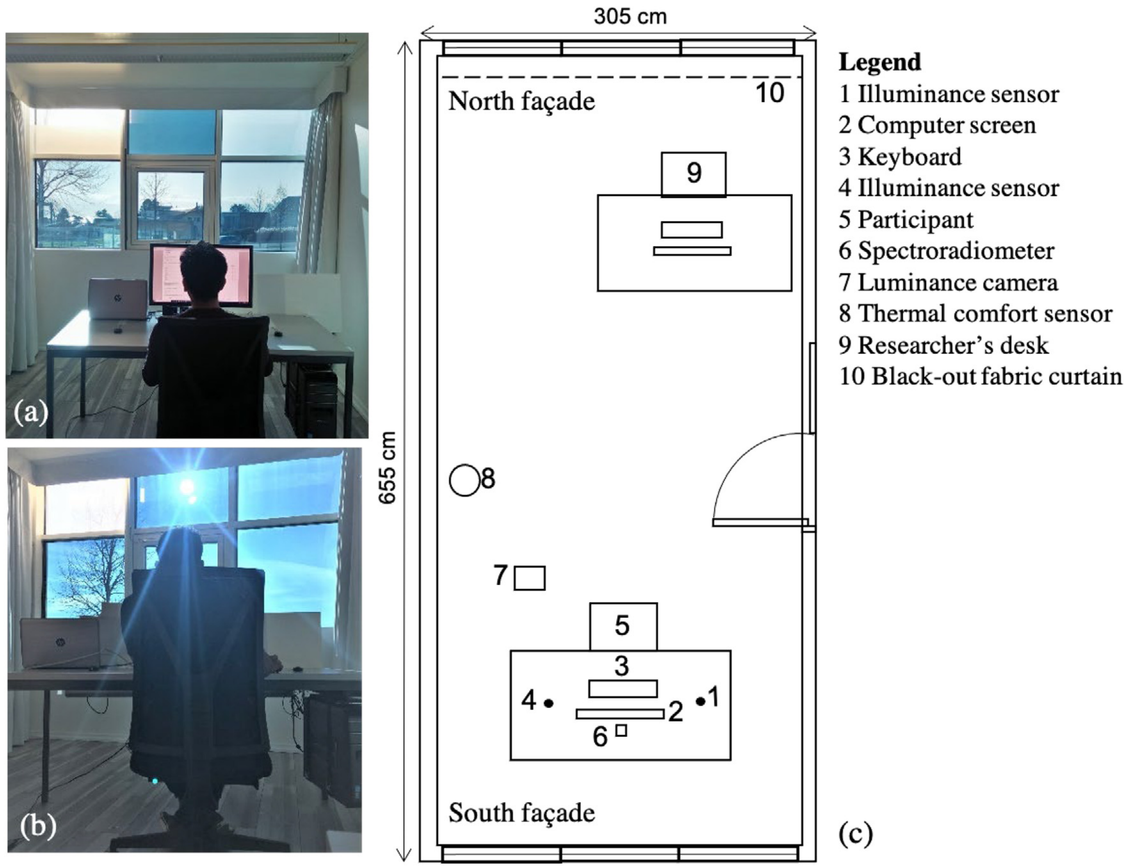


Fig. 1. (a) and (b) Participants performing the experimental task in the test room in one of the example cases, (c) Test room layout

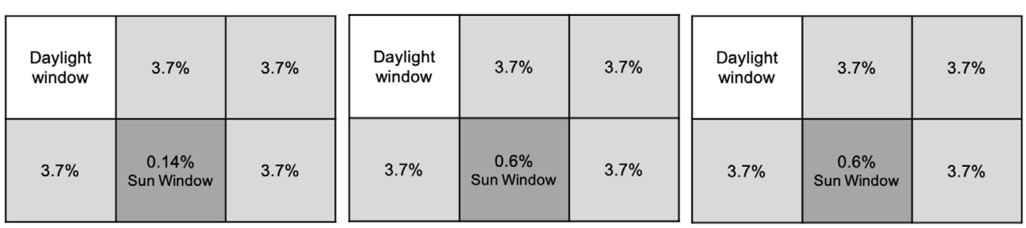


Fig. 2. EC glazing configuration example showing the measured $\tau_{v,\ n\text{-}h}$ values for the three levels of transmittance tested.

than 0.001. The measurements were conducted after reaching stable window conditions and were repeated several times. We report the average measured values in Table 1.

These values were further confirmed by other two methods: one based on a ratio of indoor to outdoor measured vertical illuminance and another based on a ratio of indoor image-derived sun disk luminance to outdoor simulated sun disk luminance using the measured direct and diffuse horizontal irradiance as input.

Table 1
Nominal, and mean measured visual transmittance of the glazing.

Nominal $\tau_{v,\ n\text{-}h}$	Mean measured $\tau_{v,\ n\text{-}h(\pm uncertainity)}$
0.2% (fully tinted + additional filter)	0.14% (±0.000147)*
0.9% (fully tinted)	0.6% (±0.001)
2%	1.6% (±0.001)
5.5% (view window)	3.7% (±0.001)
59% (fully bleached)	56% (±0.001)

* measurement uncertainty for 0.14% level is calculated by adding the uncertainity for the EC glazing of 0.6% and for the additional filter of 22%.

The latter method used the occurring experimental conditions of all experiments of this study and confirms the levels of transmittance used in the experiments.

2.4. Test conditions

We exposed the participants to four visual scenes in randomized order. By modifying the transmittance of the EC glass from which the sun was visible to the participant (labelled "Sun window" in Fig. 2), we were able to vary the luminance of the sun from one scene to another. The scenes also varied according to the subject's viewing direction in relation to the sun. These four scenes consisted of three pre-defined levels of transmittance for the sun window ($\tau_{v,\ n\text{-}h}$ of 0.14%, 0.6% and 1.6%) and two viewing directions. We varied participant's viewing direction by rotating the desk in relation to the sun position (glare source) to achieve two configurations: (1) with the sun close to the central FOV of the test person (labelled "C"), and (2) with the sun visible in peripheral FOV of the test person (labelled "P"). In the "C" direction, the desk was oriented in a way, that the sun, the center of the computer screen and test person build a plane ("azimuthally aligned"). We made sure that for both configurations, the sun would stay visible from the same window (i.e., no shade from the frame) in the participant's FOV throughout the testing time. We varied the viewing direction only for the 0.6% transmittance level.

One EC-glazing pane (labelled "Daylight window" in Fig. 2) was kept in the bleached state ($\tau_{v,\ n\text{-}h}$ = 56%) to limit possible colour rendering problems in the room and to keep the minimum illuminance level within 300 lx on the participant's desk. Four remaining glazing panes were set to $\tau_{v,\ n\text{-}h}$ = 3.7%. Glazing configuration was set in a way to have the daylight window as far as possible from the participant's field of view to avoid glare from the daylight window. We positioned the desk so that the sun patch resulting from the daylight window was kept outside the FOV of the participants. The location of the sun window and daylight window varied throughout an experiment depending on the time of the day. During all the tests conditions, the sun was visible through the upper middle window in 45% of the cases, through the lower east window in 22% of the cases, through the upper east window in 21% of the cases and through the lower middle window in 12% of cases.

Following is the naming convention to refer to each visual scenario:

- "1.6C": $\tau_{v,\ n\text{-}h}$ of the sun window of 1.6% and sun in the participants' central FOV
- "0.6C": $\tau_{v,\ n\text{-}h}$ of the sun window of 0.6% and sun in the participants' central FOV
- "0.6P": $\tau_{v,\ n\text{-}h}$ of the sun window of 0.6% and sun in the participants' peripheral FOV
- "0.14C": $\tau_{v,\ n\text{-}h}$ of the sun window of 0.14% and sun in the participants' central FOV

These scenarios are presented in the HDR fisheye-images shown in Fig. 3.

We conducted a series of pre-test measurements with HDR imaging to decide on our visual conditions. The final scenarios were chosen because the calculated discomfort glare did not overlap with each other. Table 3 describes the visible transmittance, the median values of the position index, sun luminance visible through the glazing, E_v, DGP, CGI, UGP and DGI calculated from the HDR images of each experimental condition.

We took additional measures to ensure that the sun was the only glare source during the exposure. If there would have been sunlight patches on the participant's desk that might be perceived as another source of glare in addition to the sun, we installed white cardboard sheets on the desk parallel to the facade to hide the patches but at the same time retain the view to the outside. Similarly, to avoid glare from the reflection of the sun on the neighboring building, a white cardboard sheet was placed covering partially the windowpane where the potential secondary glare source would have been visible.

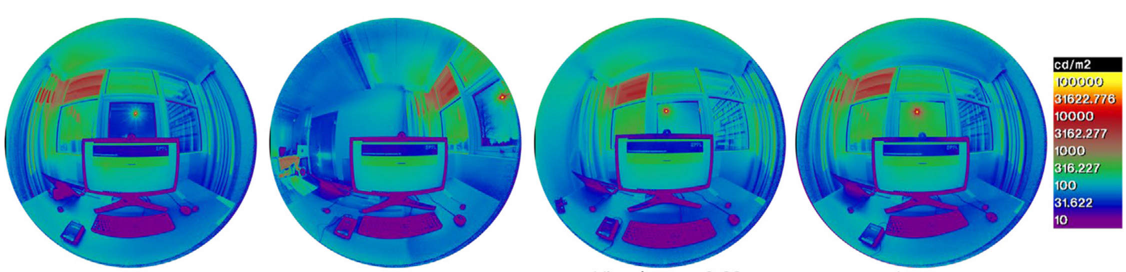
Before starting the participant's exposure to each visual scene, we made sure that the glazing had completely switched to the pre-defined transmittance level by monitoring the feedback from the control system. It took up to 12 min to switch the glazing transmittance from the highest to the lowest transmittance level and vice-versa.

2.5. Experimental procedure

The experiments were conducted between 8:30 and 13:30 on days with a sunny clear sky from December 2019 to February 2020. The total duration of each experimental session was about two hours and a maximum of two sessions could be conducted in a day, with one participant at a time. Participants were selected following the inclusion criteria mentioned in section 2.1.

The experimental procedure is visualized in Fig. 4. The first step (introduction) was conducted under electric light with curtains closed. After arriving in the test room, the participant was briefed about the experiment following a single-blind procedure to avoid response bias. They were not informed about the specific objectives of the study but were given a broad description of the experiment which was pre-written and read by the researcher for all the participant so that every participant received the same level of information.

The exposures phases were conducted after an introductory phase that included the task description by the researcher, the signing of the consent form by the participant, and the completion of a background questionnaire. The four exposure phases were identical. Each of them started with a break time in which the test persons were given an eye mask to cover their eyes and headphones to listen to music and relax. During the break time, the researcher took measurements (of the visual conditions that preceded or followed) and prepared the room for the upcoming phase by changing the window glazing transmittance and re-arrange the participants' desk as needed for the next visual scene. During the exposure phases, the participants were asked to type a predefined text on the computer for five minutes which allowed them to visually adapt to each visual condition and to simulate a working environment. The text given to the participants was varied through all the visual scenarios and the texts were evaluated to have the same level of readability (checked with [38]). Afterwards, the participants filled out an exposure questionnaire on their visual and thermal level of comfort. The HDR camera was adjusted to the participant's eye position while seated and images were taken before and after each scene. The exposure to each scene took about 12 min (including typing task and exposure questions). The relaxation time between the scenes took also about 12 min, but it should be noted that the time interval required to change and stabilize the glazing transmittance sometimes prolonged the break duration between each scene. At the end of the session, the participants filled out a debriefing questionnaire to report their overall comfort perception and view satisfaction. Indoor environmental parameters (see 2.2) were measured continuously during the whole experiment. The order of the four visual scenes was randomized among participants to avoid anchor point bias [39].



Visual scene 0.14C Visual scene 0.6P Visual scene 0.6C Visual scene 1.6C

Fig. 3. HDR falsecolor fisheye-images of four visual scenarios presented to participants

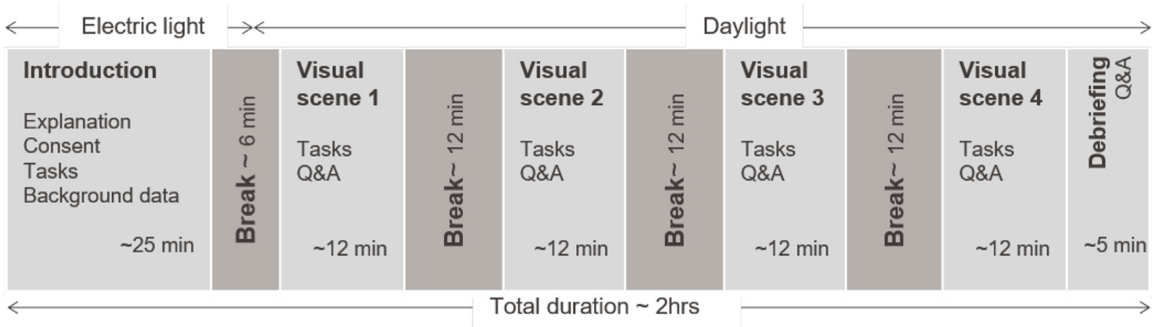


Fig. 4. Experiment Procedure

2.6. Subjective assessment

The participants provided their subjective feedback by completing a web-based questionnaire presented to them on the computer screen. There were three sets of questionnaires used during the experiment: 1) a background questionnaire once at the beginning of the experiment, 2) an exposure questionnaire after the exposure to each visual scene and 3) a debriefing questionnaire at the end of the experiment.

Background questions were asked during the introduction phase to collect baseline data for each participant. The questions were about demographics (e.g., age, gender, eye colour), their current mood, feelings and physical state, their sensitivities, and preferences towards certain indoor environmental parameters such as heat, cold, bright light, view to the outdoors. These questions were included to evaluate potential confounding factors, if any.

Exposure questions were asked after the typing talk during the exposure to each visual scene. It included questions on discomfort from glare, lighting level, colour perception, thermal comfort and satisfaction regarding the indoor environmental conditions. The questions were answered on binary, categorial (Likert) or ordinal scales. The questions pertaining to discomfort glare perception are listed in Table 2. They were either directly taken from or adapted from previous studies with an aim to minimize the potential response bias that can be created by the rating scales. Discomfort glare was evaluated on more than one scale to compare the internal consistency between the scales and the reliability of the responses. Our first question is an open-ended text field that allows participants to describe their negative (disturbing) sensations without forcing them to select from pre-defined options or drawing their attention to a particular comfort parameter. It has been highlighted by the previous studies that rating scales usually do not have *'no glare'* option which forces an opinion leading to the possibility of overestimating the discomfort glare when there is no discomfort and also, the uncertainty over the meaning of response labels may result in incorrect evaluations [40,41]. To address such distortions, our second question uses a binary glare scale (with *Yes/No* options) adapted from Pierson [42]. This question possesses an appended branching asymmetrical four-point Likert scale (that only pops up in case of discomfort glare report) which is not analysed in the paper. Question 3 asks about glare perception on the widely used *Osterhaus scale* in glare studies [43] using four categories. As question 2 was the first that explicitly included the word "glare", we provided the participant with a definition ("glare is an excess of light inducing annoyance or discomfort"), that we found useful to familiarize participants with the concept of glare and to maintain the same basic understanding of glare for all participants.

Participants' written answers to the open-ended question were converted into a binary glare. If they indicated glare or sun or the contrast from light and dark areas as the disturbing elements, then the answer was converted as "1″, otherwise as "0" on a binary scale.

At the very end of the experiment, debriefing questions were asked to inquire about the overall comfort of the participant during the experiment. It included questions on view satisfaction and clarity, thermal and visual comfort, acoustics, and air quality in the room during the entire experiment.

This paper focuses on discomfort glare evaluations and therefore includes only a brief evaluation of other parameters to ensure that they do not bias results. For our analysis, we considered two categories of potential confounding factors that might influence subjective discomfort glare responses based on previous literature [44]: environmental factors, related to the experiment set-up, and personal factors, related to the participant's physical and psychological conditions. We addressed these potential confounding factors by keeping them constant (e.g., age group, room temperature, view through the window, task difficulty, season, previous luminous environment), or by measuring them (e.g., optical correction, iris colour, self-assessed glare sensitivity, physical state, emotional state)[46].

Table 2
Subjective glare estimation questions.

Question	Response scale
1. Is there anything about the physical environment that disturbs you in this moment?	*Open-ended text field*
2. At the moment, do you feel discomfort due to glare?	Yes – No
If answered "Yes", then following question is asked: **2.1** How much discomfort do you feel due to glare at the moment?	Slight discomfort – Moderate discomfort – Large discomfort – Unbearable discomfort
3. How do you rate the current glare from the window?	Imperceptible – Noticeable – Disturbing – Intolerable

2.7. Data cleansing

We established three rules/criteria to ensure reliability and robustness of the data collected: (1) stable sky conditions throughout an exposure (i.e., no intermittent clouds occluding the sun), (2) the sun is not hidden at any time by the window frame or other elements from participant's FOV during the experimental phase, and (3) the sun is the only glare source visible in the participant's FOV. Rule 1 was implemented by comparing the images captured before and after exposure to each scene. Rule 2 and 3 was implemented by checking the output from the Evalglare tool [14] on each processed image in terms of the number of glare sources in a scene and luminance of glare sources. For this, we used the -b option in the Evalglare and set the glare detection threshold at 50000.1 cd/m^2 while disabling peak extraction using the -x option

Table 3
Median values of visual properties and glare models of the four experimental conditions.

Scene	$\tau_{v,n,n}$ measured (Sun window)	Sun disk luminance (cd/m^2)	Viewing angle (degrees)	Position index	Ev (Lux)	DGP	CGI	UGP	DGI
1.6C	1.6%	17,050,000	25.5	2.4	1650	0.5	49.59	0.85	30.32
0.6C	0.6%	5,137,300	25.8	2.5	1054	0.41	41.93	0.79	27.06
0.6P	0.6%	4,689,800	58.1	6.2	702	0.36	37.07	0.74	21.50
0.14C	0.14%	1,108,000	29.2	2.5	692	0.32	33.25	0.68	22.42

to detect only the sun and to make sure it is not hidden by window frame and there are no reflection of the sun (i.e. a second sun) in the scene. This approach is specific to our experimental conditions where we have the sun at a low angle as the only glare source. We calculated the glare metrics by default Evalglare algorithm that consider a threshold of 2000 cd/m^2 for glare source detection.

All the HDR images were also checked for pixel overflow (saturation of pixels). Fourteen images of scene "1.6C" were found to have a slight pixel overflow. In such scenarios, measured vertical illuminance values were higher than the image-derived vertical illuminance values. These images were corrected by replacing the overflow pixels matching the measured vertical illuminance. In one case, the measured vertical illuminance value was found to be lower than the image-derived value due to the shading of the lux sensor from the window frame, therefore, the before described method could not be applied. Instead, we selected first a reference area (ring around the sun) seen through the sun window where there was no overflow and which was visible as well in the scene just before or after, where there was no overflow at all. The luminance ratio of the two median values of that area was multiplied by the luminance value of the non-overflow sun disk pixels and used to replace the overflow pixels (16 pixels in total).

2.8. Statistical methods

Descriptive statistics were used to summarize the measured environmental parameters. The values of mean, median, standard deviation, and interquartile ranges are presented through boxplots, and tables. We used Spearman's rank correlation [47] as a statistical method to determine the effectiveness of the glare metrics in predicting the subjective glare perception as the response scale has an ordinal character. The Spearman's rank correlation is a non-parametric test that measures the rank-based association between two variables instead of their raw value. The effect size or the strength of the correlation between two variables were determined by the Cohen's effect size thresholds [48] which consider correlation coefficient $\rho > 0.3$ as a medium effect, and $\rho > 0.5$ as a strong effect. We considered using the more conservative effect size thresholds proposed by Ferguson [49], yet, the cross-validation study on glare metrics [15] mentioned earlier showed that, when comparing the correlation analysis with Receiver Operating Characteristic (ROC) analysis, Cohen's effect size thresholds are in better agreement with ROC interpretations [50] than the one from Ferguson.

We also applied the ROC curve analysis to evaluate the ability to discriminate between glare and no-glare situations. ROC curves plot the true positive rate (TPR or sensitivity) against the true negative rate (TNR or specificity) which indicate the prediction rate. The AUC value (area under the curve) is another performance indicator showing the ability to distinguish between the two levels of a binary variable (here glare or no glare), with a higher value corresponding to a better prediction model. Regarding the interpretation of the AUC value, Hosmer-Lemeshow [50] categorizes values > 0.7 as acceptable, values > 0.8 as excellent and Safari et al [51] describe values between 0.6 and 07 as poor. We further use Delong's test [52] to check if two ROC curves are significantly different from each other. The number of data points in this study was relatively small compared to the number of data points needed to calculate reliable thresholds. Therefore, this analysis is not intended to derive specific thresholds but is only used to represent a tendency towards a certain direction.

3. Results

A total of 80 data points was gathered by exposing 20 participants to four visual scenarios. However, after a strict verification of the data and a thorough examination of HDR images and vertical illuminance measurements of all the scene following the rules detailed in section 2.6, we removed 7 data points to ensure the reliability of the data collected. The remaining 73 data points are analysed and the results are presented in the subsequent section.

3.1. Indoor environmental conditions

Garretón et al showed that thermal comfort had an impact on subjective glare when the people were outside their thermal comfort zone [53]. We have therefore considered this parameter as a possible confounding factor. The ambient temperature and relative humidity of the room were kept within a comfortable range during the entire test period, as shown in Table 4. Participants also reported their thermal sensation on the 7-point ASHRAE scale (ranging from "cold" to "hot" with "neither cold nor hot" as a central vote). Answers indicated that 91% of the votes were in the three intermediate options ("slightly cold", "neither cold nor hot", "slightly hot") and no votes at either end of the scale (cold/hot), which confirms the good thermal comfort of the participants during the experiment.

We used the average of the two lux sensors placed on the left and right of the participant's desk to inform on the horizontal illuminance levels at the participant's desk. These sensor locations were chosen to avoid sensor-shading by the participant. Lighting levels are mostly within the comfortable ranges following the lighting standards as shown in Table 4. Similar to the subjective reporting of thermal comfort, participants also reported their perception of the lighting levels on the desk on a 7-point Likert scale ranging from ("very low" to "very high" with "just right" as a central vote). 94.5% of the votes range within the three middle options ("slightly low", "just right", "slightly high"), confirming that the lighting levels at the desk stayed within a comfortable zone.

3.2. Discomfort glare evaluations

3.2.1. Test conditions

Our four aforementioned visual scenarios differ in terms of luminance of the glare source, vertical illuminance and position index. They are discussed in this section in relation to values calculated from the HDR images, the measured vertical illuminance and glare metrics. Table 3 presents an overview of all the scenes in terms of mean values of sun disk luminance, glare metrics, position index and viewing angle between the sun and centre of the image. To validate the accuracy of HDR images, the vertical illuminance calculated from the images are compared with the ones measured using a hand-held illuminance meter (Fig. 5 left).

Table 4
Descriptive statistics values for the indoor environmental parameters.

Scene	Desk illuminance (lux)				Vertical illuminance at eye level (lux)				Room air temperature (°C)	Relative humidity (%)
	0.14C	0.6P	0.6C	1.6C	0.14C	0.6P	0.6C	1.6C		
Mean	690	766	609	704	722	937	1014	1543	22	38.5
Median	448	619	503	549	692	702	1054	1650	22.3	39.9
Max	1850	1670	1645	1750	1144	3484	1413	1878	23.9	43
Min	195	256	175	180	289	351	410	848	20.5	30
SD	454	411	354	435	242	742	323	309	1.28	3.49

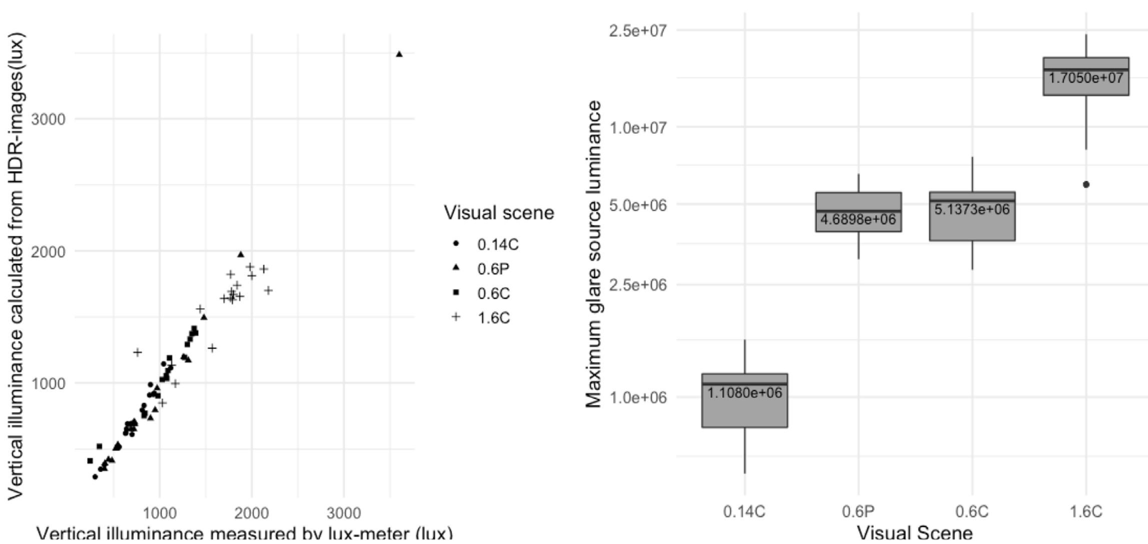


Fig. 5. (left): Comparison of measured and image-derived vertical illuminances for different visual scenes. The RSME between the calculated and measured values is 73 lux (normalised 7%), and the normalised bias is 1.3% (corrected images were not considered). (right): Boxplots indicating the sun disk luminance for each scenario across all tests. We indicated on each box the median value for the considered scenario.

Fig. 5 (right) shows the sun disk luminance (cd/m2) in each visual scenario for all tests as boxplots. We observe that the scenarios, which differentiate from each other by the window transmittance, overlap very little, which was our goal. The intensity of the sun luminance directly relates to the sun window transmittance used in the experiments: "1.6C" being the highest, "0.14C" being the lowest, and "0.6P" and "0.6C" being halfway and showing a similar range of luminance (they differ in position index).

Position index and viewing angle in relation to glare source in each scene category are compared in Fig. 6 (left). The position index considers the horizontal and vertical displacements of a glare source from the line of vision of the observer. The goal of the experiment setup was to create the scenarios in critical (sun in the roughly central visual field: 1.6C, 0.6C, 0.14C) and non-critical viewing directions (sun in the peripheral visual field: 0.6P). As seen in Fig. 6 (left), the median position index values of the critical viewing direction reside within the same range whereas the "0.6P" situation has significantly higher and spread-out values. Since there were geometrical constraints regarding shading through the deep frames and the small-sized windows the position index values are more dispersed in the "0.6P" category. Similarly, the median viewing angle for "C" scenarios lies between 25 and 30°whereas for "P" scene, it lies at 58°.

Fig. 7 (left) presents a comparison between the daylight glare probability (DGP) values of the four visual scenarios in a box plot indicating the median DGP values in each scene. The DGP cut-off value used to distinguish between disturbing and non-disturbing glare used in the European standard EN17037 is 0.40 [6] and 0.38 as calculated in the cross-validation study [15]. Considering these values, the median DGP values shown in Fig. 7 can be used to classify quantitatively the scenario "0.6P" and "0.14C" as non-disturbing and scenario "0.6C" and "1.6C" as disturbing. The subsequent section discusses the results from the subjective perception of glare in each of these scenarios.

We also compared the calculated vertical eye illuminance for each visual scenario across all test cases using boxplots (see Fig. 7 right). As expected, E_v is not a suitable variable to distinguish the different scenes shown by the large overlap of the box plots.

3.2.2. Participant's responses to glare exposure

We analysed the subjective responses pertaining to glare reported by the participants for each visual scene (procedure described in section 2.5.1). Fig. 8 presents the relative frequency of subjective glare votes on a 'yes'/'no' scale. In general, the subjective responses show a similar trend as the mean DGP values examined in the previous section. Scene 1.6C has the highest number of votes in the discomfort category among all the scenes indicating the inability of a window with $\tau_{v,\ n\text{-}h}$ = 1.6% to minimize the glare for 89% of the participants when the sun is close to the central vision. For similar sun positions and a $\tau_{v,\ n\text{-}h}$ of 0.6% (scene 0.6C), 53% of the participants reported the situation causing discomfort due to glare. For similar sun positions and a $\tau_{v,\ n\text{-}h}$ of 0.14% (scene 0.14C), only 16% of the participants reported discomfort due to glare. When the sun was visible in the peripherical FOV and for a $\tau_{v,\ n\text{-}h}$ was 0.6% (scene 0.6P), 21% of subjects reported discomfort due to glare, which confirms the impact of the index position compared to scene 0.6C.

Similar results can be observed evaluating the subjective response on the Osterhaus four-point scale (see Fig. 9). In addition to the fact that this scale uses four categories as response options,

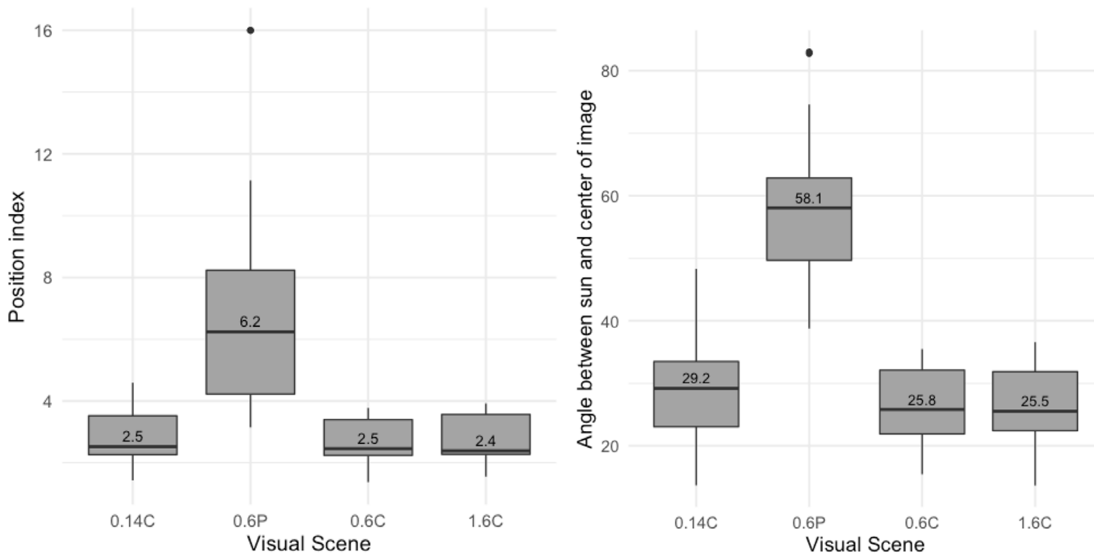


Fig. 6. (left): Position index comparison between the four visual scenes. We indicated on each box the median values for the considered scenario, (right): Viewing angle comparison between the four visual scenes. We indicated on each box the median values for the considered scenario

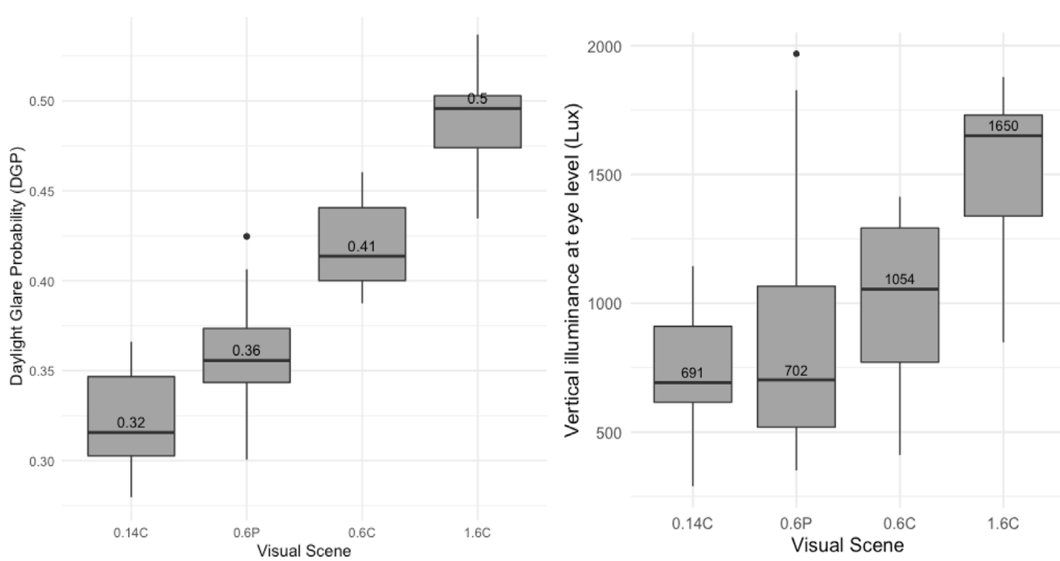


Fig. 7. (left): Daylight glare probability values, (right): Vertical illuminance at eye level for each visual scene

another difference from the binary scale is the semantic difference between the labels ‘‘discomfort" (binary-scale) and ‘‘disturbing" (Osterhaus-scale). This semantic difference could explain why participants exposed to scene 1.6C reported only 50% of disturbing (or intolerable) glare, while they reported 89% discomfort glare. Scene 0.6C on the Osterhaus scale presents an interesting distribution of votes when compared to the votes on the binary scale in Fig. 9.

Of all the participants who voted ‘‘noticeable" glare on the Osterhaus scale, 58% had voted" Yes" on the binary glare scale. This demonstrates that the label ‘‘noticeable" does not translate to an absence of discomfort for a significant number of participants. This underlines the importance of semantic differences of glare scales and becomes important when applying thresholds or ROC analysis, which will differ when quantifying ‘‘avoidance of discomfort" or ‘‘avoiding of disturbance". The latter is e.g., used for existing thresholds of DGP.

The results for critical low sun positions allow us to conclude that limiting the sun disk luminance to around 5 million cd/m^2 (corresponds to a $\tau_{v,\ n\text{-}h}$ of 0.6%) can prevent disturbing glare for most users but does not provide a comfortable situation. To avoid discomfort from glare the sun disk luminance should not exceed 1 million cd/m2 (this was achieved by a $\tau_{v,\ n\text{-}h}$ of around 0.14%) for such sun positions. These results are also in line with the previous study done by Lee et al. which suggest a $\tau_{v,\ n\text{-}h}$ of 0.1% for controlling glare [24]. For non-critical viewing direction, the results suggest that limiting sun disk luminance to around 5 million cd/m^2 being sufficient to achieve visually comfortable space for a majority of participants (79%). This was achieved by using a $\tau_{v,\ n\text{-}h}$ of 0.6% for the tested blue tinting EC-glazing. This angular dependent glare sensitivity outcome is explained by the directional sensitivity of the photoreceptors, known as the Stiles-Crawford effect, [54] when light entering the eye through the centre of the pupil is about five times brighter than the light entering through the edge of the pupil and which is expressed by the position index P in existing glare metrics.

We also note that visual comfort could be reached with a higher glazing transmittance of the ‘‘Sun window" in case all the other

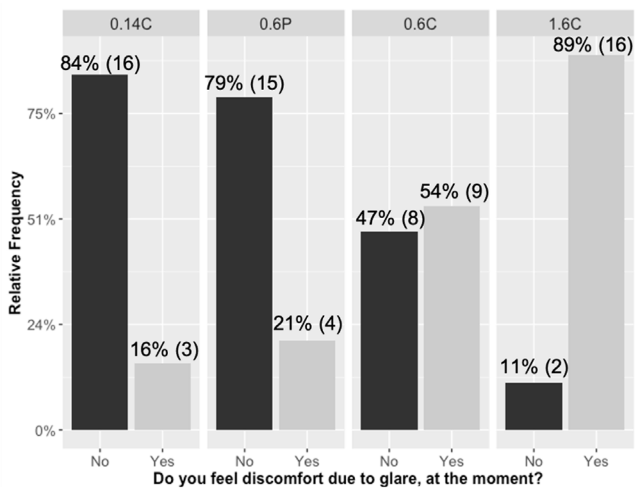


Fig. 8. Comparison of subjective glare responses on binary scale

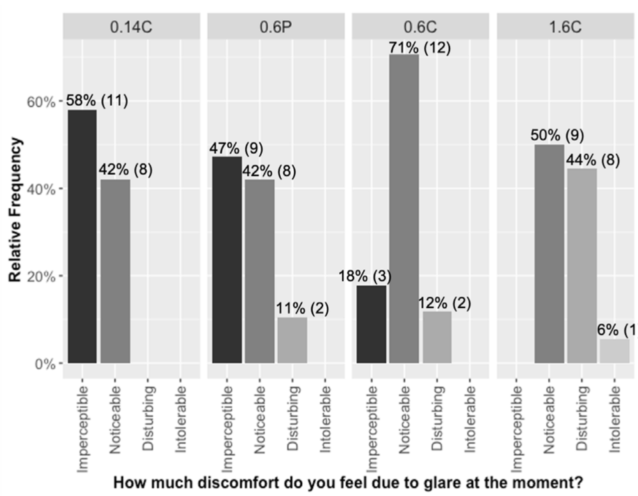


Fig. 9. Comparison of subjective glare responses on Osterhaus scale

windows were set to a higher transmittance, resulting in higher adaptation level and therefore, reducing the contrast. However, the vertical illuminance levels in this study are higher than in usual workplace situations [42] and therefore, this scenario is less likely to happen in practice. The vertical illuminance both informs the saturation of the glare source and the adaptation levels. Conversely, if all other windows would have been set to a low transmittance, in that case lower transmittance threshold of the "Sun window" would have been expected to avoid discomfort from glare. This scenario is also unlikely because of the necessity of providing sufficient horizontal illuminance levels on the desk.

3.2.3. Discomfort glare metrics performance and thresholds

To evaluate the effectiveness of glare metrics in predicting subjective responses we applied first Spearman's rank correlation using the responses to the Osterhaus scale. Five glare metrics are investigated, namely DGP, CGI, UGP, DGI, and vertical illuminance at eye (E_v) calculated by using Evalglare [55] on the HDR images. The ρ-value for DGP, CGI, UGP and DGI are in a similar range (0.559–0.595), whereas E_v was calculated to 0.43.

For the second performance evaluation, we conducted a ROC analysis and the resulting AUC value. The AUC calculated from the ROC analyses shows the ability of a metric to distinguish between discomfort and comfort situations respectively between disturbing and non-disturbing situations in terms of glare.

Each point on the curve presents a cut-off or threshold value and an optimal threshold can be calculated by determining the point on the curve which has the shortest distance from the top left corner of the graph. Table 6 and Figure 10 present the AUC and threshold values determined for the discomfort glare metrics DGP, CGI, UGP, E_v and DGI. Two different threshold values are calculated for each metric using the binary scale and converting the Osterhaus scale to binary scale (Imperceptible & Noticeable = No glare, Disturbing & Intolerable = Glare) However, it should be noted that due to the limitation of the number of data points, this analysis cannot be relied upon to provide accurate results. The results from this analysis only indicate the overall tendency of the data.

Both performance evaluations show that all metrics using the contrast effect in their equation (DGP, CGI, UGP, DGI) deliver highly reliable results. For Spearman's correlation and following Cohen's standard [48] for the effect size these metrics show a strong effect size. The AUC values indicate for them an excellent discrimination.

As expected, the performance values for E_v are lower, indicating a moderate effect size and a discrimination ability at the borderline between poor and moderate. Due to the small sample size, none of the differences between the r values shown in Table 5 can be proven as significant (hittner2003 test of the cocor package[56] retains the null hypothesis with a p-value of 0.0614 for a one-tailed test). However, the Delong's test [52] comparing the AUC values on the binary scale showed even with the low sample size a significant difference between E_v and the rest of the glare metrics at a significance level of 0.01. The low performance of E_v can be explained by the inability of solely saturation-based metrics to capture the extreme luminance of the sun in FOV while having a low transmittance of the façade. This result underlines that for the evaluation of EC glazing a glare metric sensitive to contrast should be used. E_v should not be used as glare metric for façade systems with low transmittance where the sun disk is still visible.

To determine, whether the "Daylight window" had an impact on discomfort glare, we evaluated the answers from the open-ended questions. From all the 73 cases, there wasn't any reported case of glare through "Daylight window" while many reported discomfort due to glare from the sun in their eyes. Furthermore, we compared the AUC results where the "Daylight window" was included as glare source with results where the "Daylight window" was explicitly excluded as glare source. Latter was achieved by using an absolute threshold of 30,000 cd/m^2 for the glare source detection in *evalglare*. We didn't find a significant difference in the AUC by applying the Delong's test. Both subjective and prediction model analysis indicate that the glare perception remains the same and that in our experiments the sun is the only glare source.

The glare thresholds for DGP found in this study (0.43) are higher than the one's reported in the cross-validation study (DGP = 0.38) [15] and EN17037 recommendations (DGP = 0.40) [6] based on dividing the Osterhaus scale responses to binary values ("disturbing" and "intolerable" votes grouped). This suggests that DGP is slightly overestimating the glare in such EC scenarios for predicting disturbing situations. This hypothesis is also supported by the results of the highest scenario 1.6C where an average calculated DGP of 0.49 already indicated "intolerable glare" whereas only 6% of the test persons indicated this level. However, more data points are needed to confirm this hypothesis. A similar tendency can be expected when using other shading strategies where the sun is visible such as the fabric roller shades that provide a view to outside.

There is also a difference between the glare thresholds when evaluated on a binary scale compared to the Osterhaus scale. The threshold for "discomfort" due to glare is lower than the threshold for the glare rated as "disturbing". This threshold for discomforting

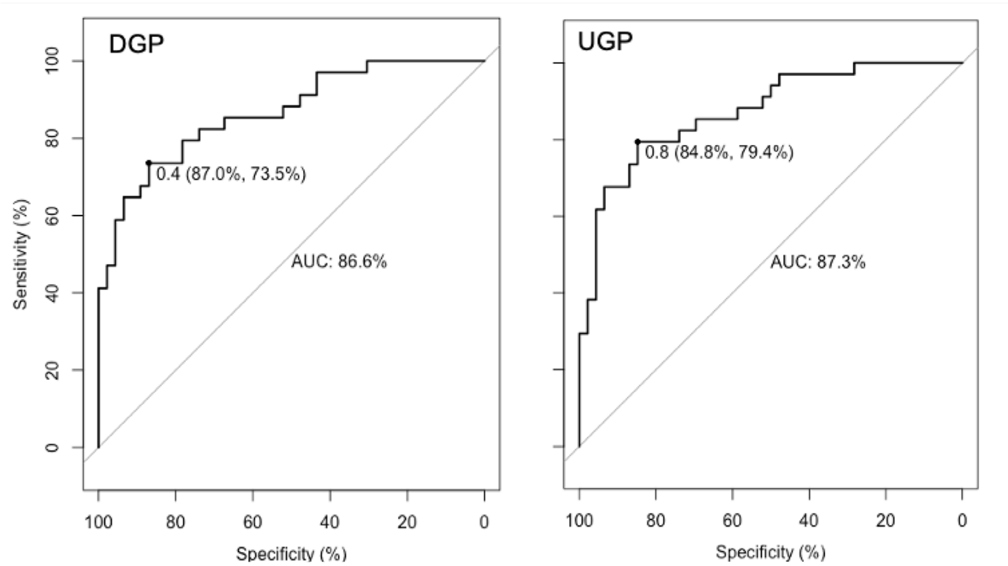


Fig. 10. ROC curve analyses for DGP and UGP showing AUC and threshold value on the binary glare scale

Table 5
Spearman correlation ρ of glare metrics in comparison to subjective responses.

	DGP	E_v	CGI	UGP	DGI
Osterhaus scale	0.60	0.44	0.59	0.58	0.56

Table 6
AUC and threshold values for blue tinting EC glazing for daylight glare metrics obtained through ROC analyses.

	DGP	E_v	CGI	UGP	DGI
AUC based on binary glare scale	0.86	0.70	0.87	0.87	0.84
Threshold for the binary (Yes/No) scale	0.40	1180	41.4	0.78	25.6
Threshold for the Osterhaus scale	0.43	1213	44.4	0.81	26.1

situations (0.4) corresponds to the threshold of the medium glare protection recommendation in EN17073.

This scale difference raises interesting questions on the level of comfort that should be achieved when designing a building. The spread of the distribution of glare responses in scene 0.6C also highlights individual differences between test persons. This has been highlighted in several previous studies [10,11,57].

4. Limitations

The limitations of this study that have an impact on the generalizability and accuracy of the results are listed below:

- The evaluations in this study are based on young healthy adults between 18 and 30 years which is not representative of a general workplace population. Therefore, the results do not apply to individuals of higher age groups and/or with certain vision limitations. As the literature [58–61] indicates, discomfort glare thresholds are expected to be lower in such cases
- The sample size acquired in the study may not be sufficient to perform ROC analysis and determine reliable threshold values (cut-off values)
- the results presented are only suggesting the tendency. As highlighted in a review study by Bujang et al., a sample of 22 persons is very small and minimum recommended sample size is 62 participants in the medical screening studies [62].
- The exposure time to adapt to each visual scene before the start of survey questions was limited to 5 min. This was done to balance the extended break time required to switch the EC glazing between the scenes. However, the exact time required to adapt to a visual scene is still unknown [42].
- The number of visual scenes evaluated are limited in their range of transmittance and position index. Scenarios having glare source between the peripheral and central FOV are not evaluated and the peripheral viewing direction is only evaluated under τ_v of 0.6%. The threshold transmittance to control glare suggested in the results are limited to the scenes evaluated and can vary significantly in different scenarios.
- Results obtained in this study are only valid for blue-tinted EC glazing and are expected to be different for other coloured and colour-neutral glazing due to the influence of spectrum on discomfort glare [63,64]. Earlier experiments done with coloured LEDs demonstrated that coloured LEDs induce more discomfort glare than white LED and among the coloured LEDs blue ones gave the highest glare perception [64]. We expect similar trends in daylit scenarios, although there are no such studies done under daylight so far.
- The HDR camera used to produce luminance maps in this study implements the CIE colour sensitivity function of the 2° standard observer [65], however, as per the literature CIE 10° standard observer function should be used to calculate luminance

for parafoveal light sources [66] that better explains the enhanced spectral sensitivity under short wavelength outside the foveal region.

- In this study, we wanted to focus on glare perception through EC glazing when sun in visible in FOV. We cannot exclude that different range of stimuli, e.g., comparing sun not in FOV or low-contrast, or diffuse conditions to our conditions might have led to a different outcome. Such scenarios should be further studied.

5. Conclusions

In this study, we evaluated the discomfort due to glare from the sun seen through blue tinting EC glazing. Twenty participants were exposed to four visual scenarios varying in sun luminance and viewing direction towards the sun in a south EC glazed office-like test room and reported their glare perception of each scene.

The results from the subjective evaluation indicate that a sun disk luminance of around 5 million cd/m^2 (corresponds to a $\tau_{v,\ n\text{-}h}$ of 0.6% for the investigated EC glazing) is sufficient to control glare when the sun is in the peripheral FOV of the participant whereas the same is not applicable in critical viewing direction (e.g., sun position within 30° cone around the fovea). For the critical viewing direction where the sun is within 30°, a sun disk luminance of around 1 million cd/m^2 (corresponds to a $\tau_{v,\ n\text{-}h}$ of 0.14% of the investigated EC glazing) was found suitable in controlling glare whereas for 16 million cd/m^2 (corresponding to a $\tau_{v,\ n\text{-}h}$ of 1.6%), 89% of the subjects reported discomfort due to glare. These results also confirm the strong angular dependency of glare perception, expressed by the position index P in the glare metrics. It must be noted that these findings are valid only for blue-tinted EC and might differ for other colored or color-neutral systems (see limitations).

For these types of scenarios, the range of the luminance of the glare source (i.e. the sun) lies between 1 and 20 million cd/m2, which must be considered when choosing a suitable HDR camera with appropriate neutral density filters to avoid pixel overflow even for higher luminance values (approx. 50–80 million cd/m^2) for the investigation of the threshold between comfort and discomfort when the sun is in the peripheral FOV and/or color neutral glazing type is measured.

The results also suggest that four (DGP, DGI, UGP, CGI) of the five discomfort glare metrics assessed in the paper have a strong correlation with the subjective response to glare with a spearman's rank correlation coefficient between 0.55 and 0.59. The ROC analysis also suggests that for such situations where the sun is visible in the field of view, these four metrics are well suited in differentiating "glare" and "no glare" situations showing an AUC in the range of 0.84–0.87 which indicated a good prediction model. Solely saturation-based metrics like E_v are not suitable to predict glare for low transmittance glazing where the sun can be seen through the façade.

Since the glare metrics and their positional sensitivity seem to be valid for the investigated lighting scenarios, further (simulation) studies should investigate the annual behavior and therefore the frequency of occurring glare for typical working environment setups to determine the lowest transmittance stage needed to achieve overall comfortable spaces.

Further experimental studies should be conducted to validate the findings, to assess the influence of blue-tinted versus color-neutral and other colored glazing and to confirm and specify higher glare thresholds suggested by our study under blue-tinted glazing. Modified glare metrics that consider these scenarios should be developed prior to implementing glare thresholds in the design guidelines.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This study is funded by the Swiss National Science Foundation (SNSF) as part of the ongoing research projects, "Visual comfort without borders: Interactions on discomfort glare" (SNSF #182151).We would like to thank M. Lagier and A. Schüler for conducting the spectral transmittance measurements. We would also like to thank Margareta Bali for her support in planning and conducting the experiments.

References

[1] P. Boyce, C. Hunter, O. Howlett, The Benefits of Daylight Through Windows, Rensselaer Polytechnic Institute, Lighting Research Center, 2003.
[2] L. Heschong, R.L. Wright, S. Okura, Daylighting impacts on human performance in school, J. Illum. Eng. Soc. 31 (2) (2002) 101–114.
[3] P. Leather, M. Pyrgas, D. Beale, C. Lawrence, Windows in the Workplace Sunlight, View, and Occupational Stress, Environ. Behav. 30 (6) (1998) 739–762, https://doi.org/10.1177/001391659803000601.
[4] A. Leaman, B. Bordass, Productivity in buildings the 'killer' variables, Build. Res. Inf. 27 (1) (1999) 4–19, https://doi.org/10.1080/096132199369615.
[5] J. Mardaljevic, L. Heschong, E. Lee, Daylight metrics and energy savings, Light. Res. Technol. 41 (3) (2009) 261–283, https://doi.org/10.1177/1477153509339703.
[6] European Committee for Standardization CEN, "EN17037:2019 Daylight in buildings," 2019.
[7] J. A. Jakubiec, "Validation of Simplified Visual Discomfort Calculations," in *Proceedings of BSO 2018*, Cambridge, UK, Sep. 2018, vol. 4, p. 7. [Online]. Available http://www.ibpsa.org/proceedings/BSO2018/1A-3.pdf.
[8] "Switchable facade technology ('swift') | SWIFT Project | FP5 | CORDIS | European Commission." https://cordis.europa.eu/project/id/ENK6-CT-1999-00012 (accessed Feb. 12, 2021).
[9] CIE, "Discomfort Glare in the Interior Working Environment," Commission Internationale de l'Eclairage, Vienna, Austria, 55:1983, Jan. 1983.
[10] R.G. Hopkinson, Glare from daylighting in buildings, Appl. Ergon. 3 (4) (1972) 206–215, https://doi.org/10.1016/0003-6870(72)90102-0.
[11] T. Iwata, M. Tokura, Examination of the limitations of predicted glare sensation vote (PGSV) as a glare index for a large source, Examination of the limitations of predicted glare sensation vote (PGSV) as a glare index for a large source Towards a comprehensive development of discomfort glare evaluation, Towards a comprehensive development of discomfort glare evaluation, Int. J. Light. Res. Technol. 30 (2) (1998) 81–88, https://doi.org/10.1177/096032719803000205.
[12] CIE Technical Committee, CIE 117–1995 Discomfort Glare in Interior Lighting, International Commission on Illumination, Vienna, 1995.
[13] H.D. Einhorn, Discomfort glarea formula to bridge differences, Light. Res. Technol. 11 (2) (1979) 90–94, https://doi.org/10.1177/14771535790110020401.
[14] J. Wienold, J. Christoffersen, Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras, Energy Build. 38 (7) (2006) 743–757, https://doi.org/10.1016/j.enbuild.2006.03.017.
[15] Wienold *et al.*, "Cross-validation and robustness of daylight glare metrics," *Light. Res. Technol.*, p. 1477153519826003, 2918, doi: 10.1177/1477153519826003.
[16] J. Wienold, "Dynamic daylight glare evaluation," in *Proceedings of Building Simulation*, 2009, pp. 944–951. Accessed Aug. 15, 2014. [Online]. Available https://www.ibpsa.org/proceedings/BS2009/BS09_0944_951.pdf.
[17] K. Chaloeytoy, M. Ichinose, and S.-C. Chien, "Determination of the Simplified Daylight Glare Probability (DGPs) Criteria for Daylit Office Spaces in Thailand," *Buildings*, vol. 10, no. 10, Art. no. 10, Oct. 2020, doi: 10.3390/buildings10100180.
[18] I. Konstantzos and A. Tzempelikos, "Daylight Glare Probability Measurements And Correlation With Indoor Illuminances In A Full-Scale Office With Dynamic Shading Controls," p. 14, 2014.
[19] Andersen and Kleindienst, "The adaptation of Daylight Glare Probability to dynamic Metrics in a Computational Setting.pdf," presented at the Lux Europa 2009 – 11th European Lighting Conference.
[20] J.A. Jakubiec, C.F. Reinhart, The 'adaptive zone' – A concept for assessing discomfort glare throughout daylit spaces, Light. Res. Technol. 44 (2) (2012) 149–170, https://doi.org/10.1177/1477153511420097.
[21] M.B.C. Aries, J.A. Veitch, G.R. Newsham, Windows, view, and office characteristics predict physical and psychological discomfort, J. Environ. Psychol. 30 (4) (2010) 533–541.

[22] J.K. Day, B. Futrell, R. Cox, S.N. Ruiz, A. Amirazar, A.H. Zarrabi, M. Azarbayjani, Blinded by the light Occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies, Build. Environ. 154 (2019) 107–121, https://doi.org/10.1016/j.buildenv.2019.02.037.
[23] M. Moeck, E.S. Lee, M.D. Rubin, R. Sullivan, S.E. Selkowitz, Visual Quality Assessment of Electrochromic and Conventional Glazings, Lawrence Berkeley National Lab, CA (United States), 1996.
[24] E.S. Lee, D.L. DiBartolomeo, Application issues for large-area electrochromic windows in commercial buildings, Sol. Energy Mater. Sol. Cells 71 (4) (2002) 465–491, https://doi.org/10.1016/S0927-0248(01)00101-5.
[25] E.S. Lee, D.L. DiBartolomeo, S.E. Selkowitz, Daylighting control performance of a thin-film ceramic electrochromic window Field study results, Energy Build. 38 (1) (2006) 30–44, https://doi.org/10.1016/j.enbuild.2005.02.009.
[26] A. Piccolo, F. Simone, Effect of switchable glazing on discomfort glare from windows, Build. Environ. 44 (6) (2009) 1171–1180.
[27] A. Piccolo, A. Pennisi, F. Simone, Daylighting performance of an electrochromic window in a small scale test-cell, Sol. Energy 83 (6) (2009) 832–844, https://doi.org/10.1016/j.solener.2008.11.013.
[28] Y. Ajaji, P. André, Thermal comfort and visual comfort in an office building equipped with smart electrochromic glazing An experimental study, Energy Procedia 78 (2015) 2464–2469.
[29] R.D. Clear, V. Inkarojrit, E.S. Lee, Subject responses to electrochromic windows, Spec. Issue Daylighting Build. 38 (7) (2006) 758–779, https://doi.org/10.1016/j.enbuild.2006.03.011.
[30] M. Zinzi, Office worker preferences of electrochromic windows a pilot study, Build. Environ. 41 (9) (2006) 1262–1273, https://doi.org/10.1016/j.buildenv.2005.05.010.
[31] Page, J.-L. Scartezzini, J. Kaempf, and N. Morel, "On-site performance of electrochromic glazings coupled to an anidolic daylighting system," *CISBAT 2005*, vol. 81, no. 9, pp. 1166–1179, Sep. 2007, doi: 10.1016/j.solener.2007.01.011.
[32] E.S. Lee, E.S. Claybaugh, M. LaFrance, End user impacts of automated electrochromic windows in a pilot retrofit application, Energy Build. 47 (2012) 267–284.
[33] R. E. Kelly, B. Painter, J. Mardaljevic, and K. N. Irvine, "Preliminary findings of a case study into the application of electrochromic glazing in a UK office," 2013.
[34] R. Kelly, B. Painter, J. Mardaljevic, and K. Irvine, "Capturing the user experience of electrochromic glazing in an open plan office," in *CIE Midterm conference–Towards a new century of Light, Paris, France*, 2013, pp. 12–19.
[35] G. Charness, U. Gneezy, M.A. Kuhn, Experimental methods Between-subject and within-subject design, J. Econ. Behav. Organ. 81 (1) (2012) 1–8, https://doi.org/10.1016/j.jebo.2011.08.009.
[36] F. Faul, E. Erdfelder, A.-G. Lang, A. Buchner, G*Power 3 A flexible statistical power analysis program for the social, behavioral, and biomedical sciences, Behav. Res. Methods 39 (2) (2007) 175–191, https://doi.org/10.3758/BF03193146.
[37] R. Steiner, P. Oelhafen, G. Reber, and A. Romanyuk, "EXPERIMENTAL DETERMINATION OF SPECTRAL AND ANGULAR DEPENDENT OPTICAL PROPERTIES OF INSULATING GLASSES," in *CISBAT Proceedings*, EPFL, Lausanne, Switzerland, 2005, pp. 441–446. [Online]. Available https://glassdbase.epfl.ch/glassdocs/2121-CISBAT2005_Oelhafen1Logo.pdf.
[38] "Measure the Readability of Text – Text Analysis Tools – Unique readability tools to improve your writing! App.readable.com." https://app.readable.com/text/(accessed Feb. 12, 2021).
[39] M. Kent, S. Fotios, S. Altomonte, Discomfort glare evaluation The influence of anchor bias in luminance adjustments, Light. Res. Technol. 51 (1) (2019) 131–146, https://doi.org/10.1177/1477153517734280.
[40] A. C. Allan, V. Garcia-Hansen, G. Isoardi, and S. S. Smith, "Subjective Assessments of Lighting Quality A Measurement Review," *Illuminating Engineering Society*, p. 12, doi: https://doi.org/10.1080/15502724.2018.1531017.
[41] S. Fotios, Research Note Uncertainty in subjective evaluation of discomfort glare, Light. Res. Technol. 47 (3) (2015) 379–383, https://doi.org/10.1177/1477153515574985.
[42] C. Pierson, Discomfort Glare Perception from Daylight Influence of the Socio-Environmental Context, Université catholique de Louvain, Louvain-la-Neuve, Belgium, 2019.
[43] W. K. E. Osterhaus and I. L. Bailey, "Large Area Glare Sources and Their Effect on Discomfort and Visual Performance at computer Workstations," in *Proceedings of the 1992 IEEE Industry Applications Society Annual Meeting*, Houston, TX, USA, 1992, pp. 1825–1829. Doi: 10.1109/Ias.1992.244537.
[44] C. Pierson, J. Wienold, M. Bodart, Review of factors influencing perceived discomfort glare from daylighting, J. Illum. Eng. Soc. N. Am. (2018), https://doi.org/10.1080/15502724.2018.1428617.
[46] J.C. Nunnally, I.H. Bernstein, Psychometric Theory, McGraw-Hill, New York, 1994.
[47] C. Spearman, The proof and measurement of association between two things, Am. J. Psychol. 100 (3–4) (1987) 441–471.
[48] J. Cohen, Ed., *Statistical Power Analysis for the Behavioral Sciences*. Academic Press, 1977. Doi: 10.1016/B978-0-12-179060-8.50017-7.
[49] C.J. Ferguson, An effect size primer A guide for clinicians and researchers, Prof. Psychol. Res. Pract. 40 (5) (2009) 532–538, https://doi.org/10.1037/a0015808.
[50] D.W. Hosmer, S. Lemeshow, *Applied Logistic Regression*. Wiley-Blackwell (2005), https://doi.org/10.1002/0471722146.index.
[51] S. Safari, A. Baratloo, M. Elfil, A. Negida, Evidence Based Emergency Medicine Part 5 Receiver Operating Curve and Area under the Curve, Emergency 4 (2) (2016) 111–113.
[52] E.R. DeLong, D.M. DeLong, D.L. Clarke-Pearson, Comparing the areas under two or more correlated receiver operating characteristic curves a nonparametric approach, Biometrics 44 (3) (Sep. 1988) 837–845.
[53] J.Y. Garretón, R. Rodriguez, A. Pattini, Effects of perceived indoor temperature on daylight glare perception, Build. Res. Inf. 44 (8) (2016) 907–919.
[54] G. Westheimer, Directional sensitivity of the retina 75 years of Stiles-Crawford effect, Proc. Biol. Sci. 275 (1653) (2008) 2777–2786, https://doi.org/10.1098/rspb.2008.0712.
[55] J. Wienold, "Evalglare–A new RADIANCE-based tool to evaluate daylight glare in office spaces," 2004.
[56] B. Diedenhofen and J. Musch, "cocor A comprehensive solution for the statistical comparison of correlations," *PLoS ONE*, vol. 10, no. 4, 2015, doi: 10.1371/journal.pone.0121945.
[57] M. Iodice, "Méthodes de caractérisation psychophysique et physiologique de l'éblouissement d'inconfort en éclairage artificiel intérieur étude de l'influence du contenu spectral des sources lumineuses," These de doctorat, Lyon, 2020. Accessed Feb. 12, 2021. [Online]. Available http://www.theses.fr/2020LYSET007.
[58] P. R. Boyce, *Human Factors in Lighting – Third Edition*. Boca Raton, USA Taylor & Francis Group, 2014.
[59] C. bennett, *The Demographic Variables of Discomfort Glare*. Lighting Design and Application, 1977.
[60] T. Iwata, M. Tokura, Position Index for a glare source located below the line of vision, Light. Res. Technol. 29 (3) (1997) 172–178, https://doi.org/10.1177/14771535970290030801.
[61] M. J. Flannagan, "Subjective and Objective Aspects of Headlamp Glare Effects of Size and Spectral Power Distribution," University of Michigan, Ann Arbor, USA, UMTRI-99-36, Nov. 1999.
[62] M. A. Bujang and T. H. Adnan, "Requirements for Minimum Sample Size for Sensitivity and Specificity Analysis," *J. Clin. Diagn. Res. JCDR*, vol. 10, no. 10, pp. YE01–YE06, Oct. 2016, doi: 10.7860/JCDR/2016/18129.8744.
[63] Michael Sivak, Brandon Schoettle, Takako Minoda, Michael J. Flannagan, Short-Wavelength Content of LED Headlamps and Discomfort Glare, J. Illum. Eng. Soc. 2 (2) (2005) 145–154, https://doi.org/10.1582/LEUKOS.2005.02.02.006.
[64] Y. Yang, R. M. Luo, and W. J. Huang, "Assessing glare, Part 3: Glare sources having different colours," *Light. Res. Technol.*, p. 1477153516676640, Dec. 2016, doi: 10.1177/1477153516676640.
[65] CIE, "Commission internationale de l'Eclairage proceedings, 1931," Cambridge Cambridge University Press, 1932.
[66] CIE publication 165:2005, "CIE 10 Degree Photopic Photometric Observer," Commission Internationale de l'éclairage, Vienna, Austria (2005), 2005.