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Discomfort glare from daylight: Influence of transmitted color and the eye's macular pigment

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ABSTRACT

Designing architectural façades that allow sufficient daylight to create visually comfortable and pleasant environments is a challenging aspect of building design. It requires accounting for visual comfort and discomfort glare risks and understanding the factors that influence them. In the last two decades, several prediction models have been developed to quantify discomfort glare by considering almost exclusively the photometric properties and spatial distribution of incoming light. Although these empirical models have been derived to best match one's perception of glare, they fail to account for the significant inter-individual variability that exists in glare perception and are furthermore limited in their applicability in certain visual environments. It is evident from the literature that not all the factors influencing discomfort glare perception are known and accounted for in the existing prediction models. Based on the literature review, we have identified two potential factors, namely, the macular pigment density in the retina and the color of daylight, as likely to influence discomfort glare perception. Up to now, their influence on glare induced by daylight has remained unknown.

To address this gap, this thesis aims to determine the influence of macular pigment density and color of the sun disc (altered by colored glazing) on discomfort glare perception in daylit environments. By means of three psychophysical experiments conducted in office-like test rooms along with the ocular examinations of the participants, we determined the influence of macular pigment and color of daylight on the perception of discomfort glare for young and healthy individuals. Three experiments were conducted, one with blue electrochromic glazing, one with color-neutral glazing, and the third with red, blue, green, and color-neutral glazing. Each experiment followed a similar protocol of exposing every participant to four daylight glare scenarios and recording their responses to questionnaires. The four daylight scenarios differed either in color or in the transmittance of the glazing through which the sun was visible as the primary glare source. The remaining windows were set in a way to keep the overall color rendering in the space as neutral as possible.

The results show that macular pigment density does not influence discomfort glare perception from the sun disc filtered by color-neutral glazing in the near-peripheral field of view. However, when exposed to the sun disc filtered by saturated blue-colored glazing also in the near-peripheral field, participants with higher macular pigment density were better able to tolerate the glare, indicating a significant influence of macular pigment in this case.

In regards to the influence of color, results show that the perceived color of the sun disc (as filtered by colored glazing) has a strong influence on participants' perception of glare. Direct sunlight filtered through four types of colored glazing of a similar visible (photopic) transmittance caused significantly different levels of discomfort glare perception amongst the participants. More precisely, participants experienced statistically higher levels of glare under the red and blue glazing compared to the color-neutral or green glazing.

The findings show that the photopic luminosity function ($V_{2°}(\lambda)$) is not an appropriate weighting function to characterize the spectral sensitivity of the human eye when a high-intensity colored glare source is in the field of view. The inapplicability of $V(\lambda)$ reinforces the need for modifications to spectral weighting in the current discomfort glare models for evaluating glare in such situations. The outcomes of this thesis have also led to a better understanding of the role of macular pigment in the discomfort glare mechanism, particularly in typical daylit environments where the light source is generally outside the fovea. The findings will hopefully be useful in nuancing development goals for future dynamic and colored glazing and, ultimately, contributing to achieving better visual comfort in indoor spaces.

Keywords: daylight, discomfort glare, color, macular pigment, user assessment, spectral sensitivity

RÉSUMÉ

La conception de façades architecturales qui laissent passer suffisamment de lumière du jour pour créer des environnements visuellement confortables et agréables est un aspect difficile de la conception de bâtiments, car elle nécessite de prendre en compte les risques de confort visuel et d'éblouissement d'inconfort et de comprendre les facteurs qui les influencent. Au cours des deux dernières décennies, plusieurs modèles de prédiction ont été développés pour quantifier l'éblouissement d'inconfort en considérant presque exclusivement les propriétés photométriques et la distribution spatiale de la lumière entrante. Bien que ces modèles empiriques aient été conçus pour correspondre au mieux à la perception de l'éblouissement, ils ne tiennent pas compte de l'importante variabilité interindividuelle qui existe dans la perception de l'éblouissement, et sont en outre limités dans leur applicabilité à certains environnements visuels. Il est évident d'après la littérature que tous les facteurs influençant la perception de l'éblouissement d'inconfort ne sont pas connus et pris en compte dans les modèles de prédiction existants. Sur la base de la revue de la littérature, nous avons identifié deux facteurs potentiels, à savoir la densité du pigment maculaire dans la rétine et la couleur de la lumière du jour, comme susceptibles d'influencer la perception de l'éblouissement d'inconfort. Jusqu'à présent, leur influence sur l'éblouissement induit par la lumière du jour restait inconnue.

Pour combler cette lacune, cette thèse vise à déterminer l'influence de la densité du pigment maculaire et de la couleur du disque solaire (modifiée par un vitrage coloré) sur la perception de l'éblouissement d'inconfort dans des environnements éclairés par la lumière du jour. Au moyen de trois expériences psychophysiques menées dans des salles de test de type bureau et d'examens oculaires des participants, nous avons déterminé l'influence du pigment maculaire et de la couleur de la lumière du jour sur la perception de l'éblouissement d'inconfort pour des individus jeunes et en bonne santé. Trois expériences ont été menées, une avec un vitrage électrochrome bleu, une avec un vitrage de couleur neutre et la troisième avec un vitrage rouge, bleu, vert et de couleur neutre. Chaque expérience a suivi un protocole similaire consistant à exposer chaque participant à quatre scénarios d'éblouissement à la lumière du jour et à enregistrer leurs réponses à des questionnaires. Les quatre scénarios de lumière du jour différaient soit par la couleur, soit par la transmittance du vitrage à travers lequel le soleil était visible en tant que source principale d'éblouissement. Les autres fenêtres étaient placées de manière à ce que le rendu global des couleurs dans l'espace soit aussi neutre que possible.

Les résultats montrent que la densité du pigment maculaire n'a pas d'influence sur la perception de l'éblouissement d'inconfort provenant du disque solaire filtré par un vitrage de couleur neutre dans le champ de vision proche de la périphérie. Cependant, lorsqu'ils sont exposés à un disque solaire filtré par un vitrage saturé de couleur bleue, également dans le champ de vision périphérique proche, les participants dont la densité du pigment maculaire est plus élevée sont mieux à même de tolérer l'éblouissement, ce qui indique une influence significative du pigment maculaire dans ce cas.

En ce qui concerne l'influence de la couleur, les résultats montrent que la couleur perçue du disque solaire (tel que filtré par un vitrage coloré) a une forte influence sur la perception de l'éblouissement par les participants. La lumière directe du soleil filtrée à travers quatre types de vitrages colorés ayant une transmittance visible (photopique) similaire a provoqué des niveaux de perception d'éblouissement d'inconfort significativement différents parmi les participants. Plus précisément, les participants ont ressenti des niveaux d'éblouissement statistiquement plus élevés sous les vitrages rouges et bleus que sous les vitrages de couleur neutre ou verte.

Les résultats montrent que la fonction de luminosité photopique ($V(\lambda)$) n'est pas une fonction de pondération appropriée pour caractériser la sensibilité spectrale de l'œil humain lorsqu'une source d'éblouissement colorée de haute intensité se trouve dans le champ de vision. Cela renforce la nécessité de modifier la pondération spectrale dans les modèles d'éblouissement d'inconfort actuels pour évaluer l'éblouissement dans de telles situations. Les résultats de cette thèse ont également permis de mieux comprendre le rôle du pigment maculaire dans le mécanisme de l'éblouissement d'inconfort, en

particulier dans des environnements normaux éclairés par la lumière du jour où la source lumineuse est en dehors de la fovéa. Les résultats seront, nous l'espérons, utiles pour nuancer les objectifs de développement des futurs vitrages dynamiques et/ou colorés et, finalement, contribuer à l'obtention d'un meilleur confort visuel dans les espaces intérieurs.

Mots clés: lumière du jour, éblouissement d'inconfort, couleur, pigment maculaire, évaluation par l'utilisateur, sensibilité spectrale.

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ABBREVIATIONS

CCT	Correlated Color Temperature
CGI	CIE Glare Index
DGI	Daylight Glare Index
DGP	Daylight Glare Probability
EC	Electrochromic Glazing
FOV	Field of View
HDR	High Dynamic Range
MP	Macular Pigment
MPOD	Macular Pigment Optical Density
PSRT	Photostress Recovery Test
SPD	Spectral Power Distribution
UGP	Unified Glare Probability
UGR	Unified Glare Index
P	Position index
ω	Solid angle
E_v	Vertical illuminance
L_b	Luminance of background
L_s	Luminance of glare source
τ_v	Visible light transmittance
$\tau_{v, n\text{-}h}$	Normal-hemispherical Visible light transmittance
$\tau_{v, n\text{-}n}$	Normal-normal Visible light transmittance
$V(\lambda)$	Photopic luminous efficiency function

PART I: INTRODUCTION

Chapter 1

Research Context

Chapter 2

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Chapter 1

Research Context

This chapter introduces the topic of discomfort glare in buildings and establishes the motivations and overall goals of the thesis.

1.1 Background

Human health is tightly interwoven with the built environment. Throughout history, buildings have been designed and adapted to enhance human health, starting with the sanitary reforms and fresh air requirements in the 19th century to combat the spread of infectious diseases and leading now to the recent focus on the impact of the indoor environment on productivity, comfort and well-being (Frumkin, 2021). The COVID-19 pandemic has further highlighted the interplay between health and the built environment and has heightened awareness of the need for healthy buildings (Li et al., 2022; Megahed & Ghoneim, 2020; Yip et al., 2021). Since the middle of the 20th century, we can see that the focus in the building sector had shifted towards reducing energy consumption and carbon emissions, particularly after the oil crisis in the 1970s, when sustainability became a priority (Hensen, 2018). In 2022, the building sector alone accounted for 34% of global energy use and nearly 37% of energy-related carbon dioxide emissions, making it a strong contributor to the threat of climate change (UN Environment Programme, 2022). As a result, significant progress has been made in implementing energy efficiency policies in building design, with a 27% increase in the number of countries introducing building energy codes since 2015. Many European countries have mandated nearly Zero Energy Building (nZEB) regulations in public office buildings since 2018 (European Union, 2016). However, these energy-focused strategies must take into account the health, well-being, and comfort of the occupants as we spend nearly 90% of our time indoors, more than any previous generation (Klepeis et al., 2001; Leech et al., 2002). The indoor environment plays a critical role in affecting our well-being (Bluyssen et al., 2011), and poor indoor environmental quality (IEQ) can even have detrimental effects on our health (WHO, 2014). Access to daylight and outdoor views through windows has been widely researched and shown to positively impact building occupants' well-being (Alimoglu & Donmez, 2005; M. Aries et al., 2015; P. Boyce et al., 2003; Dolgin, 2015). Daylight is a valuable and non-polluting source of energy that provides numerous benefits for human health and well-being.

Daylight can transform a space into a psychologically uplifting experience and is often considered a driving force in the conception of buildings from an architectural perspective (Corrodi & Spechtenhauser, 2008). The use of daylight, when combined with efficient control systems, has been reported to reduce the lighting and heating energy needs of a building by 10% to 25% (Shen & Tzempelikos, 2012; Jain & Garg, 2018). Nevertheless, the health benefits of adequate exposure to daylight extend far beyond its energy benefits, as evidenced by numerous studies published in recent years. The effects of daylight exposure and outdoor views on faster recovery of patients in a healthcare facility were first studied by Ulrich (Ulrich, 1984) and have been confirmed by several studies that followed (J.-H. Choi et al., 2012; Joseph, 2006; Schweitzer et al., 2004). Daylight has also been associated with alleviating stress and improved productivity at workplaces (Beute & de Kort, 2018; Fisk, 2000; Leaman & Bordass, 1999). Favoring daylight over electric light has been reported as conducive to higher visual satisfaction and acceptance of a space (Borisuit et al., 2015). From a physiological perspective, the recent discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs) has further strengthened the role of daylight in regulating the circadian rhythms in the human body (Berson et al., 2002; Hattar et al., 2002). Besides enabling vision, light controls the internal body clock, thereby regulating the sleep-wake cycle, effecting alertness and hormone production. Furthermore, studies have shown that suitable exposure to daylight can improve sleep, reduce depression, help night-shift workers adjust their sleep cycle, and improve overall health (Blume et al., 2019; Boubekri et al., 2014, 2020).

However, despite these numerous benefits, designing with daylight is a far more challenging task than with electric light due to its highly variable and often unpredictable nature as well as its associated issues such as overheating and glare from windows. Excessive or insufficient daylight can result in discomfort glare, which, if prolonged or recurrent, might reduce occupants' well-being, mood, and work performance, for instance. Glare is repeatedly reported as a common source of disturbance by building occupants (M. B. C. Aries et al., 2010) and has been associated with reduced productivity (Day et al., 2019a). Glare can also lead to a degradation of visual performance, eye fatigue, and headaches (W. K. E. Osterhaus, 2005). A recently published study assessing visual ergonomic risks conducted at 217 workplaces with computer screen-dominated tasks reported that the frequency of eye strain and musculoskeletal strain, especially neck pain, increased with higher glare risks in 66% of the workplaces (Hemphälä et al., 2021). All these issues can be directly or indirectly associated with glare from windows and often cause occupants to block daylight out by closing the blinds (Inoue et al., 1998), which, as often happens in the absence of an acute problem, are not actively re-opened and thus remain closed for a long duration even when daylight conditions have returned to being comfortable (O'Brien et al., 2013). Therefore, to maximize the positive impacts of daylight, it is necessary to minimize the likelihood of discomfort glare from daylight.

The first step towards addressing the problem of glare is an evidence-based understanding of what causes or influences discomfort glare. This knowledge will help improve the prediction of glare and provide more reliable information when it comes to effective daylight optimization strategies, including the design of building facades and shading devices.

1.2 Discomfort glare

1.2.1 Definition

The standard definition given by European Committee for Standardization (CEN, 2011) is the following:

Glare is defined as a condition of vision in which there is discomfort (discomfort glare) or a reduction in the ability to see details or objects (disability glare), caused by an unsuitable distribution or range of luminance or extreme contrasts.

Additionally, the Lighting Handbook of the Illuminating Engineering Society of North America (IESNA, 2000) states:

Glare is the visual sensation that occurs when the luminance within the visual field is greater than the luminance to which the eyes are adapted and, as a result, can impair vision or cause discomfort (Rea, 2000).

Glare has had many different meanings and categorizations depending on the profession referring to it, as highlighted by Mainster and Turner (Mainster & Turner, 2012). In the literature, we can find mainly five types of glare being mentioned: disability glare, dazzling glare, scotomatic (photostress) glare, veiling glare, and discomfort glare:

- Disability glare is the loss or reduction in visibility and visual performance in the presence of bright light sources in the field of view (CIE, 1983a).
- Dazzling glare occurs when bright environments spread high illuminance across large retinal areas that produce squinting, annoyance, aversion, and visual disability (Mainster & Turner, 2012; Vos, 2003).
- Scotomatic or photostress glare causes after-images and visual disability when a bright but localized light exposure excessively bleaches macular pigments in the retina (Glaser et al., 1977).
- Veiling glare occurs when the glare source is seen indirectly through reflection, such as when light falling on a monitor screen obscures the display (Jakubiec & Reinhart, 2012).
- Discomfort glare, of interest in the context of this thesis, causes visual irritation or annoyance without necessarily impairing the vision as defined by International Commission on Illumination (CIE, 1983a).

As opposed to other types of glare, we understand very little about the underlying mechanisms of discomfort glare (P. Boyce & Wilkins, 2018). Discomfort glare from daylight can be generally experienced in several contexts, for example, intense reflections of the sun off a building in an outdoor environment, excessive brightness from the large windows in an indoor environment, and strong contrasts in dim daylit spaces (Jakubiec & Reinhart, 2012).

As there is still no solid scientific explanation behind the process of generating the sensation of discomfort glare (Pierson, 2019a), most of the knowledge and literature on discomfort glare is built upon subjective surveys that ask people their perception of discomfort glare. Based on these subjective evaluations, glare prediction models are generally developed, which are further detailed in the subsequent section.

1.2.2 Prediction Models

To evaluate and address discomfort glare, it is essential to have reliable and accurate prediction models of discomfort glare. Discomfort glare metrics (or models) have several applications in many professions that include the field of architecture, lighting design, automobiles industry, and street lighting to name a few. Several lighting simulation engines implement glare metrics to evaluate specific lighting scenarios (Jakubiec & Reinhart, 2011; G. Ward, 1997). Additionally, glare metrics are used as a control trigger for the automation of shading devices (Chaiwiwatworakul et al., 2009; Colaco et al., 2012; Wu et al., 2017). Research in the area of daylight glare metrics has also greatly impacted standards and guidelines in defining the recommendations for shading devices and smart glazing technology for achieving visually comfortable spaces (CEN, 2019).

Given the wide range of applications of glare metrics, it can be hard to select the right model of discomfort glare for a given purpose. When it comes to those considered in the literature as being relevant to daylighting, there exist over 20 metrics that evaluate discomfort glare (Pierson, 2019a), which have all been derived from psychophysical studies aiming to establish a relationship between the physical stimuli and the subjective assessment of the stimuli, and which have typically been conducted in controlled lab environments. The subjects in these studies have generally been asked to evaluate their degree of perceived discomfort glare while being exposed to a lighting scenario by responding to questions based on given glare rating scales. These scales included, most commonly, either of the following: De Boer's scale (De boer, 1967), Hopkinson's scale (Hopkinson, 1972), the Glare Sensation Vote (GSV) (Iwata et al., 1992), and/or the Osterhaus-Bailey's scale (W. Osterhaus & Bailey, 1992).

Since there is no clear knowledge of the physiological factors behind experiencing discomfort glare, glare is approximated by accounting for one or two of the main effects that have been empirically observed to induce discomfort glare: saturation and contrast (Hopkinson et al., 1966). Saturation, in this context, is associated with conditions in which the total amount of light reaching a subject's eyes is too large to adapt to it; contrast, on the other hand, refers to situations where discomfort occurs because of stark differences between the luminance of light sources to the surroundings. Generally, existing glare models are based on photometric quantities that define either contrast or saturation effects (or both in the case of hybrid models), and on geometrical quantities that define glare source size and relative position in the Field Of View (FOV). As per the International Commission on Illumination or CIE (CIE, 1983a), the physical quantities required to evaluate discomfort glare are 1) the luminance of the glare source, 2) the adaptation level (luminance of background or vertical illuminance at the eye), 3) the size of the glare source (in steradians), and 4) the position index, derived based on vertical and angular displacement of the glare source from the viewing direction (Luckiesh & Guth, 1949). Based on these four quantities, several daylight discomfort glare models have been proposed in the literature. Amongst the most widely used ones, we will explain the following ones in further detail below that are either based on accounting for the contrast effect or the saturation effect or both the effect as a hybrid model: Daylight Glare Index (DGI), CIE Glare Index (CGI), Predicted Glare Sensation Vote (PGSV), Daylight Glare Probability (DGP) and Unified Glare Probability (UGP).

The first glare index to calculate discomfort glare from windows in daylit conditions, named the DGI, was developed by Hopkinson (Hopkinson, 1972) and later modified by Chauvel et al. (Chauvel et al., 1982). It is expressed as:

$$\boldsymbol{DGI} = 10\, log_{10}\, 0.478\left(\sum \frac{{L_s}^{1.6}{\Omega_s}^{0.8}}{L_b + 0.07\omega_s^{0.5} L_s}\right) \qquad (1\text{-}1)$$

where L_s is the luminance of the glare source (cd/m^2); ω_s is the solid angle of the source; and Ωs is the solid angle (sr) subtended by the glare source modified by P (position index derived from Lukiesh and Guth, 1949 (Luckiesh & Guth, 1949)); L_b is the luminance of the background (cd/m^2).

The CIE Glare Index or CGI was developed by Einhorn (Einhorn, 1979b) and accepted by the CIE commission (CIE, 1983a). It uses both direct illuminances from the glare source (E_{dir})and indirect vertical illuminances E_i=E_v-E_{dir} and is expressed as:

$$\boldsymbol{CGI} = 8log2 * \frac{1+\frac{E_{dir}}{500}}{E_i + E_{dir}}\left(\sum \frac{L_s^2 \omega_s}{P^2}\right) \qquad (1\text{-}2)$$

Later on, the Predicted Glare Sensation Vote or PGSV was proposed by Iwata et al. (Iwata et al., 1992, 1992) as a prediction of reported glare perception by people. It explicitly separates saturation from contrast glare through distinct formulae, each expressed as:
if $L_s/L_b > L_{ave}/L_{ad}$ (with $L_{ave} = E_v/\pi$),

$$\boldsymbol{PGSV_{Contrast}} = log_{10}\left(\frac{L_s^{3.2}{\omega_s}^{-0.64}}{L_b^{0.61-0.79 log\omega}}\right) - 8.2 \qquad (1\text{-}3)$$

if $L_s/L_b \leq L_{ave}/L_{ad}$ (with $L_{ave} = E_v/\pi$),

$$\boldsymbol{PGSV_{Saturation}} = log_{10}\left(\frac{-3.87}{1+(L_{ave}/1250)^{1.7}}\right) + 3.3 \qquad (1\text{-}4)$$

where L_{ave} is the mean luminance of the visual field (cd/m^2), L_{ad} is the adaptation luminance (cd/m^2) and E_v is the vertical eye illuminance (lux). PGSV values range from 0.5 to 3.5, which corresponds to going from just perceptible glare to just intolerable glare. The position index is not included in this formula because the glare source, which is the window, is expected to be always in the subject's line of vision.

The Daylight Glare Probability model or DGP was introduced by Wienold et al. (Wienold, 2010; Wienold & Christoffersen, 2006a) and expresses the probability of a person getting disturbed by glare based on user studies in office setups with daylight from the lateral windows (no zenithal openings) and with venetian blinds as a shading device. It also introduces vertical eye illuminance as the adaptation level. The formula consists of two main terms, where the first represents the saturation effect (based on E_v) and the second the contrast effect of glare, to which a constant is added:

$$\boldsymbol{DGP} = 5.87e^{-5}\,\boldsymbol{E_v} + 9.18e^{-2}\,log(1 + \sum \frac{\boldsymbol{L}^2 \omega_{5.8^\circ}}{\boldsymbol{E_v}^{1.87} P^2}) + 0.16 \qquad (1\text{-}5)$$

DGP values range from 0 to 1, in which values above 0.35 have been empirically categorized as Noticeable glare, values above 0.40 as Disturbing glare, and values above 0.45 as Intolerable glare, based on (Wienold, 2010). A recent and comprehensive cross-validation study conducted on the data derived from seven daylight glare studies run by various authors in different parts of the world has been able to show that DGP seems to be the most reliable – in the sense of having the best correlation with subjective assessments – among all 22 metrics considered relevant for daylighting (Wienold et al., 2019a).

CIE developed Unified Glare Ratings for evaluating discomfort glare from small electric light sources in 1995 for personal office spaces (CIE, 1995) and therefore, it did not apply to large-sized daylight sources. UGP was proposed by Hirning et. al (Hirning et al., 2017) by modifying Unified Glare Rating (UGR) to predict discomfort glare in open-plan offices with daylight. The data used to develop the model was based on a field study, rather than in controlled conditions such as those from which previously discussed models have been derived. In the field study, both electric light and daylight were used, although for the model development the data where glare was reported from electric light was removed. UGP is expressed as:

$$\boldsymbol{UGP} = \frac{1}{\left(1+\frac{2}{7}\left(\frac{1}{L_b}\sum\frac{\omega_S L_S^2}{P^2}\right)^{-1/5}\right)^{10}} \qquad (1\text{-}6)$$

Amongst this selection, we should note that DGI, CGI, UGP and $PGSV_{Contrast}$ are all glare models dominated by the contrast effect. $PGSV_{Saturation}$ alone is dominated by the saturation effect, while DGP is a hybrid model that considers both contrast and saturation effects.

1.2.3 Limitations of prediction models

The daylight discomfort glare models shortly introduced above were all empirical models designed to best match the characteristics of the luminous environment (photometry and geometry) to report subjective glare perception under which they were developed. Since each model was developed under a limited range of daylighting conditions and with a selected sample population, they cannot cover every lighting scenario or every individual's specific characteristics. These models typically fit well to scenarios that are inside the range of stimuli in which they were developed but it can result in poor performance when the models are applied to the stimuli outside their development data. Additionally, most models do not intend to reproduce the individual perception– for example, DGP predicts the probability of a person getting disturbed by glare. This can result in discrepancies between the different studies when comparing subjective assessments to glare predicted based on the luminous environment as soon as the studies differ in the daylighting conditions they were conducted under or the sample population they relied on (Eble-Hankins & Waters, 2005a; M. Kent et al., 2017). In an attempt to explore the various limitations of glare models, we can divide these into two main areas:

The inability of models in capturing inter-individual variability: While the empirical glare prediction models allow a reasonable estimate of the average discomfort for a group of observers, they are poor predictors of individual discomfort [Mainster and Turner 2012]. Several studies have reported a wide range of glare responses for the same daylight condition (and therefore the same glare metric value), indicating large inter-individual variability (Bian & Luo, 2017; Konstantzos & Tzempelikos, 2017; Van Den Wymelenberg, 2013; Yamin Garretón et al., 2018). Figure 1-1 shows two such examples of large scatter between subjective responses and glare metric values. It can be observed that the significantly different glare situations, as quantified by DGP, are rated the same, indicating that discomfort glare metrics do not perform consistently for each subject. This also shows that subjects can have different tolerances towards glare, which is unexplained by the prediction models. According to Loe et al., these inconsistencies in glare prediction models will persist as long as the origin of the discomfort glare remains insufficiently understood (Loe, 2016).

The inability of models in capturing certain lighting environments: In addition to the variability in the responses, current glare models also fail to predict glare perception under certain lighting scenarios, namely those which are significantly different from the ones under which the models were developed. For example, several studies with colored LEDs and headlamps have shown that the glare sensitivity of humans varies between blue-colored and color-neutral LEDs, which is not yet captured by current glare models (Fekete et al., 2010; Flannagan, 1999b; Yang et al., 2018): a poor correlation was reported between the current glare metrics' predictions and the collected subjective glare responses under these colored lighting conditions. There are also no existing prediction models applicable to the zenithal light sources. Another example is the poor prediction of glare by DGP under dim lighting conditions, such as the ones found in open-plan offices, a limitation that has been highlighted by several studies (Hirning et al., 2014; Isoardi et al., 2012; Quek et al., 2021).

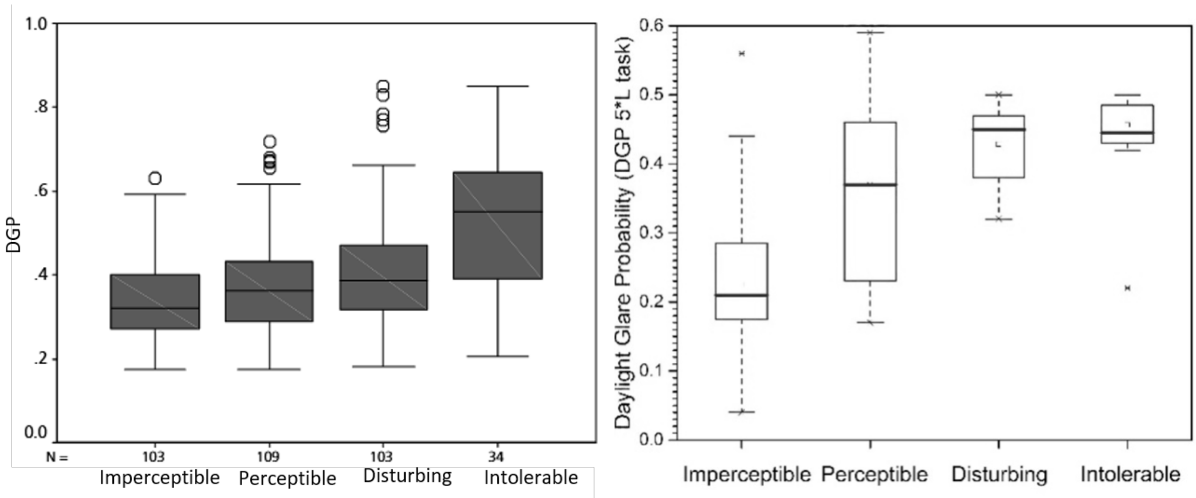


Figure 1-1 Example boxplots from two studies showing the scatter between the predicted glare metric values and subjective assessment of glare (left: (Wienold, 2010) and right: (Bian & Luo, 2017))

These shortcomings indicate that to more accurately quantify glare perception, there is a need to move beyond the parameters commonly implemented in glare models. Potential physiological and environmental factors that might influence discomfort glare from daylight should therefore be further investigated and if found to impact glare perception, they should be integrated into discomfort glare metrics to increase their prediction potential.

1.3 Overarching goals of the thesis

To contribute to a sensible integration of daylight in buildings and harvest its numerous benefits towards well-being and energy savings, it is necessary to minimize discomfort glare risks induced by daylight penetrating in indoor spaces. Glare prediction models offer the potential to anticipate glare risks but have to do this reasonably well so that designers can rely on them to inform their decisions when it comes to daylighting control strategies in buildings. However, despite the numerous efforts dedicated towards having accurate models in the last 50 years, existing models fail to account for the significant inter-individual variability that exists in glare perception and are furthermore limited in their applicability in a number of visual environments.

Building up from suggestions made by Fisher in 1991 (Fisher, 1991) and which stay pertinent today, we hypothesize that advances in discomfort glare research can be made by conducting investigations in two main areas:
i) Unveiling overlooked physiological mechanisms that may explain the experience of discomfort glare, and
ii) Establishing new empirical relationships that may exist between discomfort glare and certain characteristics of the luminous environment but have not yet been included in the prediction models, thereby limiting the applicability of these models in such environments.

The research presented herein precisely aims to contribute to both of these two areas by investigating the influence of specific physiological and environmental factors on glare perception from daylight that would be identified as having a high potential in explaining, at least partially, the observed inter-individual variability regarding glare sensitivity and/or the inadequacy of existing models to reliably predict glare in diverse luminous environments.

The overall goal of this thesis is thus to first identify and then investigate selected factors that may influence discomfort glare but have not been studied in detail yet, in order to improve and extend the applicability of the glare prediction models on which daylight optimization strategies could be based.

To achieve this goal, we will first conduct a literature review to identify the most promising factors that are known to influence glare and yet are not included in prediction models, by assuming they have the potential to explain some of the variability observed in glare perception. The identified factors will then be investigated in-depth by means of user assessment studies, to evaluate their impact on daylight-induced discomfort glare evaluation.

Chapter 2

State of the Art

This chapter presents the synthesis of current literature on the factors influencing discomfort glare and identifies the most promising factors that could be investigated for their influence on discomfort glare with an aim to improve the current understanding of the topic in general and of glare prediction models in particular. The first section (section 2.1) provides an overview of literature pertaining to the potential factors influencing discomfort glare and ends with the identification of two of the most relevant factors (i.e. macular pigment and color of daylight) that were selected for further investigation, both for their high potential in influencing glare from daylight but also because they would contribute to addressing the two limitations discussed previously in section 1.2.3. The subsequent sections 2.2 and 2.3 present a detailed discussion of the literature associated with these two selected factors. The last section (section 2.4) provides a summary of the identified research gaps which led to the research questions that became the core focus of this thesis.

2.1 Factors influencing discomfort glare

Discomfort glare perceived by occupants depends on several factors and it is evident from previous research that not all the factors are known and accounted for in existing glare models. Section 1.2.3 has proposed a summary of the two main, global limitations of these models: i) inability in capturing large inter-individual variability in glare perception owing to the fact that the physiological rationale of experiencing glare are unknown and ii) inability in capturing certain daylighting environments due to lack of studies in such environments. Therefore, to provide a more reliable and accurate measure of discomfort glare, a possible approach would be to review the factors likely to influence discomfort glare, other than the established factors already included in the models. The aim of this literature review is therefore to determine:

- What factors have been studied in the literature for their influence on discomfort glare yet have not so far been included in glare prediction models?

- What is the nature of their influence and, among these factors, which ones are the most promising to investigate?

A comprehensive review of such factors influencing discomfort glare perception has already been done by Pierson et al. (Pierson et al., 2018a), that very comprehensively presents the current understanding of all relevant factors affecting discomfort glare. As can be seen in this review, the factors influencing discomfort glare can be divided into three broad categories: Environmental and contextual factors (factors related to the observer's surrounding environment), personal and physiological factors (factors related to the observer) and study-related factors that can impact the findings when not controlled. Figure 2-1, based on (Pierson et al., 2018a), illustrates the stacked bar plots indicating the number of studies found in the literature that investigated the influence of additional relevant factors in the mentioned three categories and whether or not an influence was found on glare perception. It should be noted that most of the discomfort glare studies investigating the factors for their potential influence on glare are conducted mainly under electric light and the use of daylight is rare and more recent. The number of studies conducted on each factor and the nature of the influence of such factors on discomfort glare can inform us whether or not a particular factor is promising to be studied further in the context of daylight. It can be observed from figure 2-1, for instance, that many of the studied factors seem to have almost no influence on discomfort glare perception, the two most obvious examples being gender and optical correction, which makes them less promising. In order to find the promising factors from this exhaustive list, we need to delve deeper into the literature and go beyond the list. The subsequent subsections summarize the state-of-the-art on factors both likely to influence discomfort glare and not accounted for yet in current discomfort glare metrics, so as to identify the most promising factors that could be further studied. We divide the subsections into three categories (Figure 2-1) mentioned before and provide a summary of the most relevant factors at the end of this section. The literature associated with the identified factors are discussed in detail in sections 2.2 and 2.3.

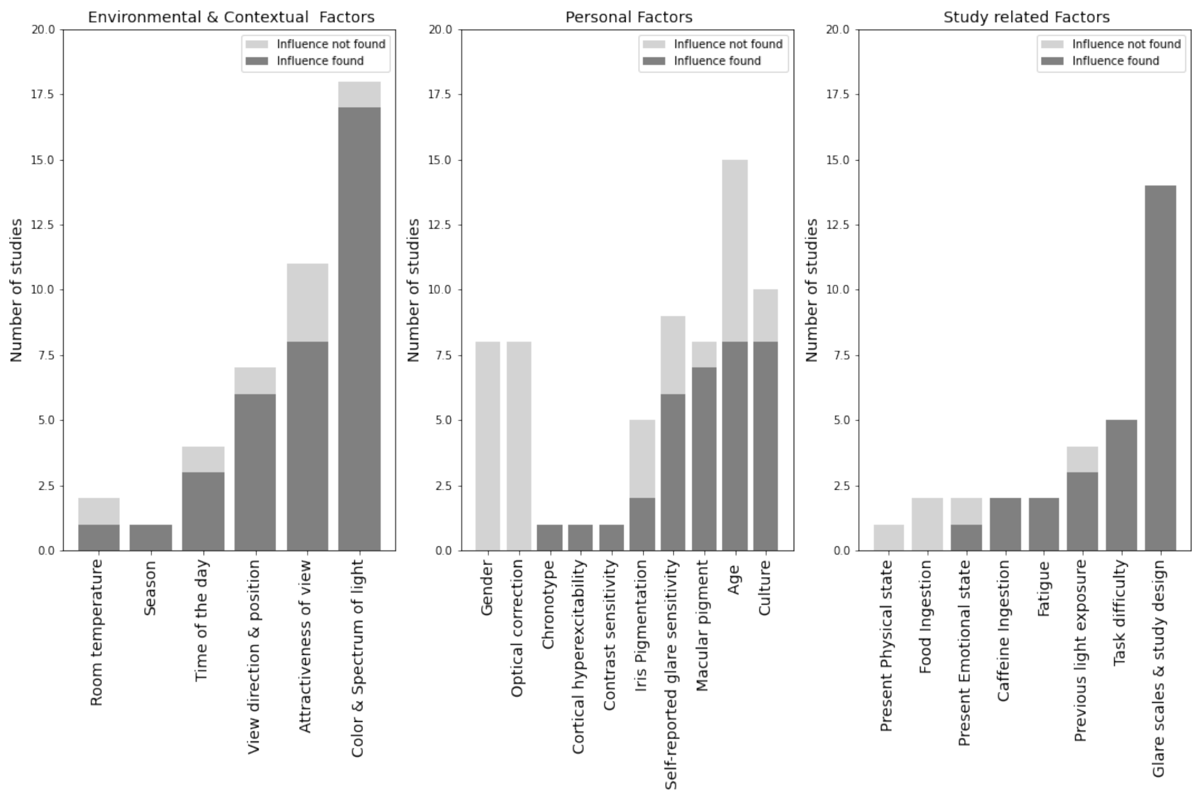


Figure 2-1 Stacked bar plot indicating the number of studies in the literature that investigated the influence of additional relevant factors and whether an influence was found or not (updated and adapted based on a review article by (Pierson et al., 2018a)).

2.1.1 Personal & Physiological factors

Existing glare models have been derived from subjective evaluations, and typically do not consider any physiological or personal factor in their equation. In visual comfort research, studied factors related to an observer are mainly their demographic or background characteristics such as age, gender, culture etc. or their visual characteristics, such as contrast sensitivity, iris color, macular pigments in the retina etc. (Figure 2-1). In this section, first, we discuss the studies conducted on evaluating the relationship between glare and the observer's background characteristics, and then we discuss the studies evaluating visual characteristics. In the end, we summarize which seem to be the most relevant factors.

Earlier studies have made observations and hypotheses on the possible influence of one's culture or socio-environmental background on perceived discomfort glare by doing inter-study comparisons conducted by different groups of researchers around the world (S. Choi & Ko, 2018; J. S. Lee & Kim, 2007; Subova et al., 1991). However, a recent study specifically focused on this topic, and that evaluated discomfort glare in Chile, Japan, Switzerland and Belgium, found no influence of culture on people's glare perception (Pierson, Piderit, et al., 2021). Several studies have also investigated the influence of age on discomfort glare, but due to conflicting findings, Pierson and others have concluded in the review that the effect of age was actually very weak and depended mainly on the visual characteristics of the participants (Akashi et al., 2017; Facchin et al., 2017; Kuhn et al., 2013; Pierson et al., 2018a). Several other studies further confirmed that both gender and optical correction of the participants were found to have no influence on discomfort glare perception (Hirning et al., 2014; Iwata et al., 1992; Saur, 1969; Shin et al., 2012; Tuaycharoen & Tregenza, 2007).

In parallel, self-assessed glare sensitivity has also been investigated in the literature as a proxy for explaining the wide variability in discomfort glare perception. Some studies did report that people assessing themselves as glare sensitive tended to report discomfort glare more often than those considering themselves non-sensitive, specifically for the glare sources in the central FOV (W. Osterhaus, 2001; Pierson, 2019a; Rodriquez & Pattini, 2014; Saur, 1969). However, this hypothesis was not confirmed by more recent studies (Inkarojrit, 2005; Rodriguez et al., 2016), which concluded instead that self-assessed glare sensitivity is not correlated with discomfort glare perception. Van Den Wymelenberg provided some nuance to this as he found that while subjects cannot judge themselves on a multiple-point scale, they can classify themselves into sensitive vs. non-sensitive on a binary scale (Van Den Wymelenberg, 2013). Given the ease of implementation, a binary question on self-assessed glare sensitivity thus seems useful to include in future experimental protocols to further confirm this hypothesis.

Several factors related to the eye and visual system have been investigated in literature with an aim to understand the physiological rationale behind discomfort glare perception. It was first investigated by Hopkinson (Hopkinson, 1956), who hypothesized that simultaneous exposure to a glare source and a dim background can cause an opposing action of the dilator and sphincter muscles in an adjustment of pupil size, resulting in a feeling of discomfort. A few other studies made a similar hypothesis, that discomfort was possibly generated as a result of pupil fluctuations (Fry & King, 1975; Vos, 2003), though this hypothesis is in contradiction with Howarth's conclusions, which did not find any significant effect of pupil fluctuations on discomfort glare perception (Howarth et al., 1993). Another suggested explanation behind glare sensation comes from the role of the trigeminal nerve in the transmission of discomfort signals from light (LEBENSOHN & Bellows, 1934; Mainster & Turner, 2012; Stringham & Snodderly, 2013), this nerve being responsible for sensations in the face combined with motor functions (such as biting, chewing). The same studies further implied that the ipRGCs, which send inputs to the trigeminal nerve, may actually initiate the discomfort signal. The role of ipRGCs in discomfort was also suggested by Amini and others (Amini et al., 2006) as an explanation for the experience of photophobia in visually blind people. Authors hypothesized that the ipRGCs' contribution could be envisaged in the photophobia mechanism of sighted people as well, which was also suggested in two subsequent studies (Bullough, 2009; Noseda & Burstein, 2011). In a similar direction, Stone proposed a theoretical model to explain the discomfort and pain in the eye induced by light, which was based on activity in the trigeminal nucleus caused by the ocular and facial response to light (Stone, 2009). However, a recent study by Iodice did not find any statistically significant correlation between the intensity of electrical activity on facial muscles measured near the eye through electromyography (EMG) and the participants' discomfort glare ratings from LEDs (Iodice, 2020). Therefore, the role of the trigeminal nerve or of pupil fluctuations in discomfort sensation remains ambiguous to date.

Factors that would be related to the brain were first studied by Bargary et al. (Bargary, Furlan, et al., 2015), who showed that people's glare sensitivity could be correlated to the degree of activity or the hyperexcitability of the neurons in the visual cortex. However, Iodice (Iodice, 2020) did again not find a significant influence of the brain signal measured through electroencephalography (EEG) on discomfort glare sensation when exposed to LEDs. The same study by Iodice also evaluated heart rate variability and collected EMG signals on facial muscles, but again did not find any statistically significant influence of these physiological indicators on discomfort glare perception. Another study by Bargary et al. (Bargary, Jia, et al., 2015) suggested that the mechanism of discomfort glare in central vision is more closely associated with spatial properties of the glare source than with the overall amount of light entering the eye, though the physiological rationale behind this could not be explained. Another studied eye characteristic is iris pigmentation: a popular belief, as mentioned by Pierson et al. (Pierson et al., 2018a), is that a lighter iris was assumed to lead to higher sensitivity to light in general than a darker iris, no statistically significant effect of iris color was found specifically on glare perception (Rodriguez et al., 2016; Stringham et al., 2011a). As far as contrast sensitivity is concerned, which is a measure of the eye's ability to identify an object not clearly defined from the background, it has been known to degrade under disability glare conditions (Abrahamsson & Sjöstrand, 1986; Puell et al., 2006); however, under discomfort glare conditions, there is only one study suggesting a possibility of an inverse relationship between discomfort glare and contrast sensitivity (Eble-Hankins & Waters, 2009).

Another factor that has been studied several times for its influence on discomfort glare, in the context of preventive care for eye pathologies, is macular pigment density in the retina (Hammond et al., 2013; Stringham et al., 2011a; Stringham & Hammond, 2008; Wenzel et al., 2006a; Wilson et al., 2021). Macular pigments (MP) are yellow dietary pigments in the fovea that aid in visual function by attenuating the blue wavelength light before it reaches the photoreceptors. Several studies have consistently shown that people with higher macular pigment density can tolerate higher levels of discomfort glare in the central (foveal) visual field. The macular pigment density varies largely in the population; therefore, it could conceivably– at least in part – be responsible for the inter-individual variability observed in discomfort glare perception. Additionally, macular pigment density is shown to degenerate with age and can thus also be responsible for age-related glare risks in the older population (Curcio et al., 1996). However, all the studies conducted on the MP and glare relationship have, up to now, been conducted only in ophthalmological settings. It is therefore still not known whether an influence can be expected under daily indoor environments and/or in daylit settings.

Besides the above-mentioned physiological factors, several studies have also explored the light-induced ocular and facial responses as an objective measure of glare, thereby complementing commonly collected subjective responses (Berman et al., 1994; Doughty, 2014; Lin et al., 2015; Yamin Garretón et al., 2015; Yamín Garretón et al., 2016). Some of these factors include the degree of eye opening, pupil size, eye movement, gaze direction, head movement and blink rate. These factors would usually be measured while a participant is actually exposed to glare during a user assessment study. Although they may not influence discomfort glare perception directly, they can potentially indicate when a person is getting disturbed. In a review article by Hamedani et al. (Hamedani et al., 2019), it was found that relative pupil size can indeed be relied upon as a reliable factor to assess discomfort glare, while factors such as gaze position and direction are found to be less reliable predictors of glare as they can be triggered by other influencing factors such as the view from window and task complexity (Sarey Khanie et al., 2016). Still, if such measures can be included easily in a user assessment protocol, they can provide useful complements to the subjective data collected and help in the understanding of people's physiological and behavioural responses when it comes to visual discomfort. Additionally, the recent AI (Artificial Intelligence) based tools and related equipment developed for eye tracking measurements have made it easier to add these kinds of measurements to the protocols thanks to the use of glasses, a webcam and/or screen-based trackers (Baltrusaitis et al., 2018; Gibaldi et al., 2017; Kassner et al., 2014).

In summary, macular pigment density has been shown to influence discomfort glare perception in the context of medical studies and, as such, become a promising factor that should be evaluated further to determine whether an influence can be observed under office settings in daylight conditions. Self-assessed glare sensitivity should also be further evaluated in user studies as a proxy for variability in discomfort glare perception. And finally, the measurement of light-induced responses such as changes in pupil size or gaze behaviour can be further evaluated for their potential as relevant indicators of visual discomfort, complementary to the more common subjective assessments.

2.1.2 Environmental & Contextual factors

Factors that were being investigated related to the observer's immediate environment and the context include season, time of the day, room temperature, view quality and view direction, and spectrum and color temperature of light (Figure 2-1). The influence of season on glare has so far been studied only by Van Den Wymelenberg (Van Den Wymelenberg, 2013) in a user study showing that subjects were more tolerant of discomfort glare in winter compared to summer. A few studies have also hypothesized that subjects have a higher acceptance of the presence of sunlight in the winter compared to the summer (Christoffersen et al., 2000; Nicol et al., 2006). Since only one study found an influence of season, Pierson et al. hypothesized that it may be associated with the observer's luminous environment before the experiment rather than with the season itself (Pierson et al., 2018a).

The influence of time of the day on glare is itself a recent topic of investigation, in which Kent et al. demonstrated that tolerance towards discomfort glare from both electric light and daylight increases as the day progresses (M. G. Kent et al., 2015; M. Kent et al., 2016, 2017; Altomonte et al., 2016). However, Borisuit et al. (Borisuit et al., 2015) did not find any difference in the participants' glare evaluations conducted over eight hours.

The influence of room temperature on glare perception, on the other hand, has only been evaluated by one study so far, (Garretón et al., 2015), which found that subjects had a different glare tolerance when experiencing thermal discomfort. A study by Chinazzo et al. (Chinazzo et al., 2019) further showed that participants were less thermally comfortable under dim daylight conditions compared to brighter daylight conditions, thus indicating a possible interaction between thermal and visual comfort.

Studies on the influence of window view attractiveness on discomfort glare perception have also shown that tolerance of discomfort glare can increase if the view from the window is attractive and pleasant (W. Osterhaus, 2001; Tuaycharoen, 2011; Tuaycharoen & Tregenza, 2007). More specifically, it was found that glare tolerance with views including natural scenes was higher than for views with urban scenes. However, Hellinga (Hellinga, 2013) found that view can only impact glare perception when it is either very bad or very good. Similarly, two other studies did not find any significant effect of view attractiveness on glare perception, since most of the study participants were satisfied with view content (Hirning et al., 2013; Iwata et al., 2017). Overall, it can be inferred that view quality and content may influence glare perception but only when occupants have a strong opinion about the view (Pierson et al., 2018a).

As opposed to other factors, spectral power distribution (SPD) and color temperature of light have been studied several times for their influence on discomfort glare perception from LEDs and vehicular headlamps. Earlier studies by Flannagan et. al (Flannagan, 1999b; Flannagan et al., 1989a), conducted with monochromatic lights of blue, green and red colors at six different peak wavelengths, have shown that the participants experienced the highest discomfort under blue lamps followed by red and green lamps. Subsequent studies on colored LEDs, High-Intensity Discharge lamps and tungsten halogen lamps reported similar results of perceiving higher discomfort glare under shorter wavelengths, while no significant difference was observed in glare perception between all other peak wavelengths of red, green, yellow and white colored light sources (Bullough, 2009; Bullough et al., 2004; Fekete et al., 2010; Kimura-Minoda & Ayama, 2011; Niedling & Völker, 2018; Sivak et al., 2005; Sweater-Hickcox et al., 2013; Yang et al., 2016). Similar findings came from studies evaluating the influence of a light source's CCT (Correlated Color Temperature) on glare perception: electric light sources with higher CCTs (blue appearance) caused higher discomfort glare than those with lower CCTs (P.-L. Chen et al., 2015; Wei et al., 2014; Zhang et al., 2013). However, none of the studies investigated the effect of colored daylight on discomfort glare perception.

To summarize, factors that were found to have a high likelihood of influencing discomfort glare perception include spectrum and color of light, while it may also be somewhat influenced by view quality and view direction, temperature, season and time of the day. However, color of light has so far not been studied in the context of daylight. Given the increasing use of colored façades, like electrochromic glazing and colored building integrated photovoltaics (BIPV) glass, it seems worth studying the influence of color of daylight (once altered by colored glass) on discomfort glare. Another important learning from the past studies conducted on the subject is that, when researchers are conducting user experiments evaluating one of the factors (such as color of daylight), they should stay attentive to control other factors (such as season or time of the day), as these may otherwise create unwanted biases.

2.1.3 Confounding factors in user studies

Confounding variables are those that affect the main experimental variables in a way that produces distorted associations between two variables. In order to achieve reliable and accurate results, it is necessary to control the possible confounding variables.

From Figure 2-1, it can be observed that out of all the study-related factors, glare scales and experimental design were found to influence discomfort glare responses in a large number of studies (Atli & Fotios, 2011; Fotios, 2009; Geerdinck, 2012; M. G. Kent et al., 2018). Since most if not all discomfort glare studies rely on glare rating scales as a measure of an individual's perception of glare, they should be carefully designed to avoid possible distortion in subjective results. Several category scales with different label names and different numbers of categories are being used in literature, such as the De Boer scale (De boer, 1967), Hopkinson's scale (Hopkinson, 1972), Glare Sensation Vote (GSV) (Iwata et al., 1992), Osterhaus-Bailey's scale (W. Osterhaus & Bailey, 1992) to name a few. The choice of a glare rating scale can sometimes influence the outcome of responses. For example, the absence of a "no glare" option in response labels can bias the subjects' answers towards an overestimation of glare (Fotios, 2015), the uncertainty in understanding response labels (e.g. the usage of the label 'just uncomfortable') or ambiguity in the interpretation of such labels can bias the responses (Allan et al., 2019), and the mixing of concepts in the responses' labels (e.g. asking about acceptance and comfort on the same scale) can also lead to distorted outcomes (Geerdinck, 2012). Additionally, the high variation in the formats used by various researchers for rating scales and questions makes it difficult to perform inter-study comparisons.

Methodological flaws in the design of an experiment can also influence the outcomes of a study. For example, an anchor point bias, created by the specific sequence in which the glare stimuli are shown to the participants, can affect their glare responses (M. Kent et al., 2019), as a learning effect can occur when several stimuli are evaluated by the participants and they are asked to perform the same task several times. This can result in inconsistent responses from the participants (Fotios, 2015). These biases can be minimized by randomizing the stimuli and limiting the number of glare stimuli evaluated by participants. The difficulty of the task performed during the experiment can also influence the participants' responses. Altomonte et al. found that difficult tasks resulted in more discomfort glare (Altomonte et al., 2016). Therefore, the task performed during the experiment should be carefully selected to minimize its influence on glare evaluation.

Other confounding factors suggested to influence glare evaluations are related to the present state of the participants during the experiment. These factors include previous lighting environment in which the participants have been, fatigue during the experiment, caffeine consumption before or during the experiments, as well as the general emotional and physical state of the participant during the experiment (Altomonte et al., 2016; M. G. Kent et al., 2015; W. Osterhaus, 2001; Pierson et al., 2018a). One way to account for the potential biases caused by these confounding variables is to restrict the similar levels of confounders across the participants: it can help, for example, to allow a dark adaptation period for all participants so that the effect of their previous luminous environment is minimized.

The research approach followed in this thesis aims to minimize the methodological flaws and possible biases by adapting certain countermeasures suggested by the literature (cf. Table 3-1) combined with careful planning of the experiments, which is further described in section 3.3.

2.1.4 Summary

This literature review of the factors influencing discomfort glare perception revealed that there is no clear understanding of the physiological rationale behind experiencing discomfort glare. Although some literature has hinted towards the role of the trigeminal nerve in the sensation of discomfort, none of the studies could provide strong findings on the topic. Another important learning is that special attention should be paid to the design of experiments and the choice of glare rating scales in order to minimize the potential biases that can negatively impact the reliability of the glare evaluation results.

Out of all the personal and physiological factors investigated in the literature, macular pigments in the retina seemed the most promising factor that can be hypothesized to partly account for the existing inter-individual variability in discomfort glare perception. In parallel, the review of environmental and contextual factors revealed that the color of light is a very promising factor when it comes to its influence on glare as it already has been shown to influence discomfort glare from electric light. Neither of them has been studied in the context of daylight, this will be the focus of this thesis.

In the next two sections (Sections 2.2 and 2.3), we will present a detailed review of the literature specific to these two factors and their relationship with discomfort glare and identify the research gaps requiring further investigations.

2.2 Macular pigment and discomfort glare

2.2.1 Optics of the eye and macular pigments

This subsection briefly describes the fundamentals of eye optics to have a baseline understanding of the composition and functioning of the human eye, which is necessary to delve deeper into macular pigment and glare interactions. After familiarizing ourselves with the basics of eye anatomy, we will focus on the macular pigment, which is the main variable of interest in this thesis. The contents of this subsection are mainly based on two books: Human Perception and Performance (Boff & Lincoln, 1988), Sensation and Perception (Goldstein & Cacciamani, 2021).

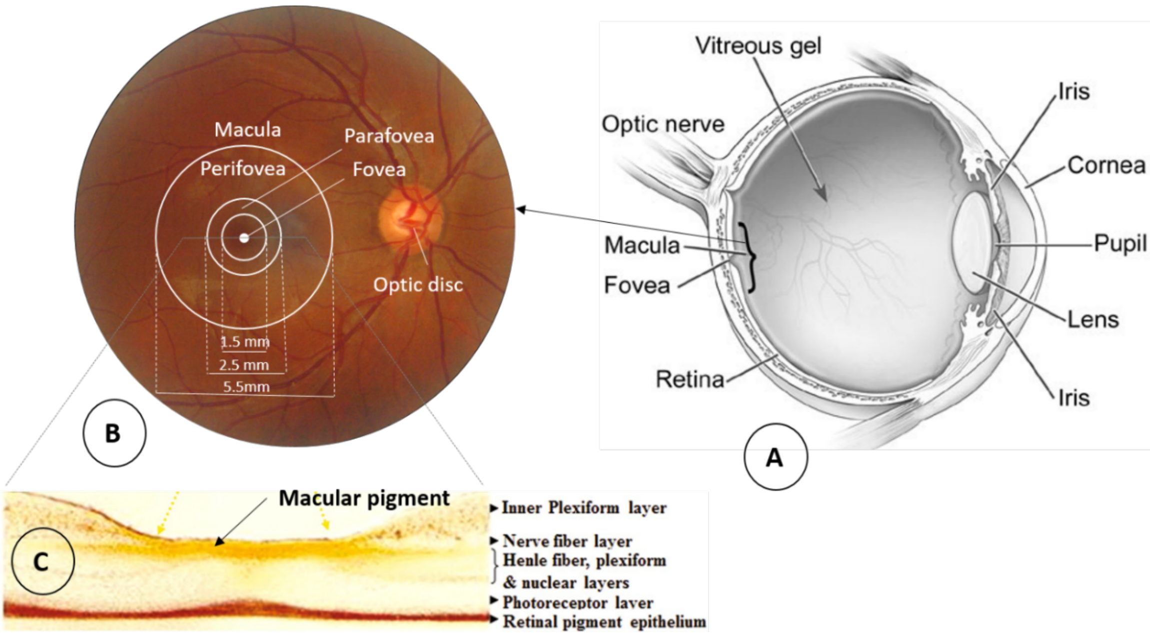


Figure 2-2 A: Anatomy of a human eye, B: Fundus photograph of the retina showing macula, optic disc, fovea, parafovea and perifovea locations, C: Cross section of the macula showing the yellow macular pigments and layers of the retina. (Figures adapted from (Arunkumar et al., 2018) and Wikipedia)

The human eye receives light through the cornea and passes it through the iris-formed aperture called the pupil. The pupil size is controlled by two opposing muscles of the iris, the dilator and the sphincter, which help in regulating the amount of light entering the eye and in the adaptation mechanism. The range of change in pupil size due to adaptation to light varies depending on the intensity of light. In bright light, the pupil size can range from approximately 1.5 to 2 mm, while in dim light, it can range from approximately 5 to 9 mm. The range of change in pupil size can also vary among individuals and can be influenced by personal factors. The light then passes through the lens and is brought to focus on the retina. The lens, by changing shape, makes it possible to adjust the focus of the eye to have a clear image on the retina for stimuli at different positions, this is known as the accommodation effect. After that, light passes through the network of nerve fibres and blood vessels that form the front layers of the retina, before it reaches the photoreceptors: rods, cones and ipRGCs. Once light reaches the photoreceptors, the optical image formed on the retina is converted or transduced into nervous impulses that can be processed by the brain. This conversion process, known as transduction, involves the photoreceptors converting the incoming light energy (in the form of photons) into electrical signals (electrical potentials). These electrical signals then travel through a network of neurons and are ultimately transmitted to the brain via the optic nerve, which is situated at the back of the retina. It's worth noting that the optic nerve is connected to the retina at the optic disc, which lacks any photoreceptors and is therefore commonly referred to as the blind spot. However, this blind spot typically goes unnoticed by the observer, except under certain special conditions.

Behind the photoreceptors, are the pigment epithelium and the choroid coat. The epithelium and the blood vessels of the choroid coat reflect light of predominantly long wavelengths back to the receptors, reducing the amount of backscatter within the eye.

In general, we can assume that the retina is organized circularly around the macula, a portion of the retina responsible for almost all of the useful photopic vision (Figure 2-2). The macula is a circular area of 2-3 mm in diameter (~ 5°-10° of visual angle) and is distinguished by yellow macular pigments. The macula includes the fovea (~1°-2° arc), a central depression that contains the highest concentration of cones but no rods and corresponds to the area where the visual acuity is the greatest.

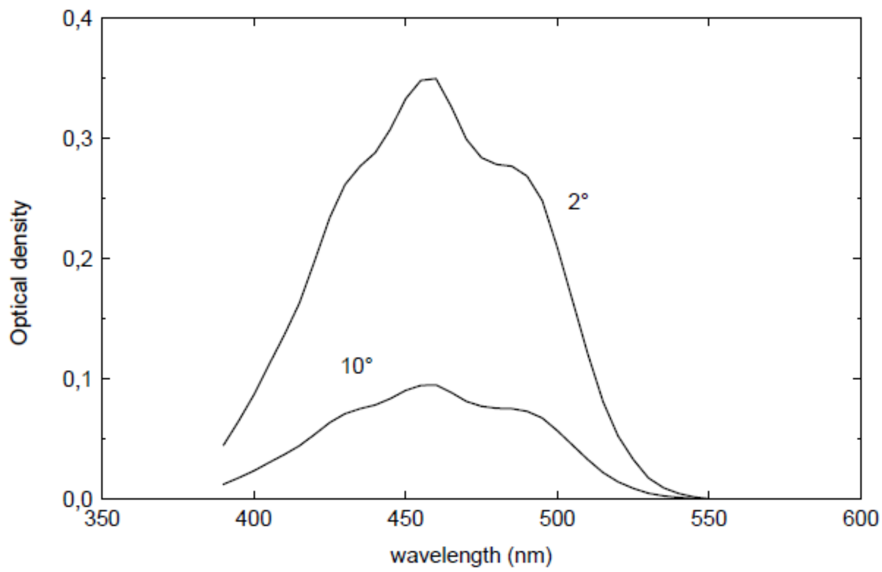


Figure 2-3 Average absorption spectrum of the macular pigment for a 2° field size and a 10° field size (CIE, 2006)

As light traverses through the eye, it passes through several layers, so not all the photons reach the photoreceptors and contribute to the vision. A large amount of light is actually scattered as it enters the eye, before reaching the retina: some light is absorbed by the cornea, lens, aqueous and vitreous humor, and some light fails to bleach the photopigment even after being absorbed. Some of the light is also filtered by the yellowish macular pigments present in the macula before it reaches the photoreceptors. The macular pigments are suggested to be a deliberate evolutionary outcome that has two broad roles: to improve visual function and to act as an antioxidant and protect the macula from damage by oxidative stress (Hammond et al., 2001b).

The yellow macular pigments mainly consist of dietary carotenoids (lutein, zeaxanthin, and meso-zeaxanthin). They are concentrated in the fovea, spreading ~3.0° along the vertical and ~6.7° along the horizontal axes, and decrease exponentially with increasing eccentricity from the centre of the fovea (Figure 2-2) (Bernstein et al., 2010). Macular pigments absorb the short-wavelength (bluish) light more than other wavelengths and thus affect the spectral sensitivity of the eye. The absorption spectrum of macular pigments lies between 400nm to 550nm, peaking around 460nm (cf. figure 2-3)(CIE, 2006). There exists a wide inter-individual variability in the amount of macular pigment across the human population, therefore causing a large variation in the amount of short-wavelength light processed by the retina (Stringham, Bovier, Wong, & Hammond, 2010). This is particularly interesting for this thesis as we wonder if this variability in sensitivity to glare could be caused by the variability in macular pigment densities. The subsequent section discusses the role of macular pigments in glare reduction and its possible influence on discomfort glare sensitivity to further refine our hypothesis.

2.2.2 Studies on the influence of macular pigment on discomfort glare

Table 2-1 summarizes the studies evaluating the influence of macular pigments in healthy subjects on their glare sensitivity. The review is limited to the studies conducted with healthy individuals which is our target sample population. All the studies conducted so far, on the influence of macular pigment in minimizing glare risks, originate from the field of medical sciences, more specifically, from the various ophthalmology journals. The literature in medical sciences often seemed to use the words discomfort glare, visual discomfort, and photophobia interchangeably, while in the building sciences, these words convey different meanings. Therefore, attention should be paid to the glare assessment methods used in the studies that can probably tell us more about what kind of glare is being measured.

As described in Table 2-1, the key findings from all the studies, except one ((Loughman et al., 2010a)), indicate that higher macular pigment density is associated with higher tolerance to discomfort glare. In addition to discomfort glare, many studies also assessed the impact of MP on disability glare and photostress recovery time (time taken to reach normal acuity after bleaching of photoreceptors by bright light) and found similar results. The reasoning behind this finding is mainly based on the filtering mechanism of the macular pigment that attenuates the chromatic aberration and reduces the scattered light reaching the photoreceptors. Most of the studies followed a similar methodology to measure macular pigment and assess glare that we describe here briefly.

For measuring macular pigment, all the studies mentioned in Table 2-3 used HFP (heterochromatic flicker photometry) method (van der Veen et al., 2009a). The HFP method is a psychophysical method different from the physical method that uses Fundus autofluorescence imaging (Delori et al., 2001). HFP is used more often than the physical method due to its ease of implementation. Generally, a macular screener device that implements HFP is used to measure macular pigment optical density (MPOD). HFP measures the attenuation of blue light by macular pigment which is linearly related to the amount of lutein and zeaxanthin in the macula. In HFP, the subject view either a centrally or parafoveal fixated target on the measuring device through an eyepiece and make flicker matches at two light wavelengths of 465nm (blue light) which is absorbed by the MP and another of 530nm (green light), not absorbed by MP. Flicker matches are made in the foveal and parafoveal region of the retina. MPOD values are measured on a scale of 0 to 1, where a lower value indicates a higher level of blue light hitting the macula. As shown in Table 2-3, all the studies have a wide range of MPOD distribution conforming to the wide variability expected in the MPOD among the population.

Table 2-1 Review of the literature on the influence of macular pigment on discomfort glare sensitivity among healthy population

Study	Sample size (age)	Light source	Angle between source and observer	MPOD distribution	Glare assessment method	Key findings
(Wilson et al., 2021)	23 (24yrs to 55yrs)	NA	NA	0.42 ± 0.14	Visual Functioning Questionnaire (VFQ-25)	MPOD was higher in subjects who reported lower ocular discomfort. (r = 0.373, P=0.040)
(Hammond et al., 2013)	150 (20yrs to 40yrs)	xenon lamp	1°	0.43±0.16	Brightness adjustment of a xenon lamp stimulus	Higher MPOD at 30' eccentricity was related to improved performance in glare. (r=0.24, P=0.0015)
(Stringham & Snodderly, 2013)	6 (21yrs to 35yrs)	xenon-white light, blue light, yellow light (440 to 600 nm)	1° (8° background source area)	0.10 to 0.71	1 (comfortable to view) to 10 (cannot view directly without much discomfort or squinting of the eyes)	MP significantly reduced visual discomfort to short wavelengths (including xenon-white light) for central viewing.
(Loughman et al., 2010a)	42 (18yrs to 41yrs)	A grating chart surrounded by 12 white LEDs (42 & 84 lux)	4.5° to 6° from central fixation	0.25 ±0.12	Visual Functioning Questionnaire	Photostress recovery and glare sensitivity were unrelated to MPOD (p > 0.05).
(Stringham et al., 2011a)	26 (23yrs to 50yrs)	White LEDs (10,000 cd/m^2)	1° (5° glare source area)	0.07 to 0.94	1-no noticeable discomfort to 10-unbearblae discomfort (5sec exposure)	Higher MPOD resulted in faster photostress recovery times, lower disability glare thresholds and lower visual discomfort (P<.05).
(Stringham & Hammond, 2008)	40 (27yrs to 41yrs)	xenon lamp	1° (5° glare source area)	0.08 to 1	Brightness adjustment of a xenon lamp stimulus	Higher MPOD were strongly correlated with improved visual performance in glare. After 6-months of L + Z supplement, glare was better tolerated
(Wenzel et al., 2006a)	10 (21yrs to 33yrs)	xenon lamp (broadband long-wave and short-wave filters)	1° (8.2° glare source area)	0.326±0.04	1-no discomfort to 10-photophobia	Higher MPOD were correlated with higher photophobia thresholds. Supplementation improved the photophobia
(Stringham et al., 2004a)	4 (25yrs to 34yrs)	xenon lamp	Centre fixation on source sized 5.6° to 28.3°	0.12 to 0.85	Brightness adjustment of a xenon lamp stimulus	Subjects with high MPOD exhibited an attenuation of Photophobia for central viewing,

For creating glare stimulus, most of the studies used a Maxwellian-view optical system with a xenon lamp that has a spectrum close to solar spectra with higher emission in the shortwave region (Stringham et al., 2004a; Stringham & Hammond, 2008; Stringham & Snodderly, 2013; Wenzel et al., 2006a). One study by Loughman et. al (Loughman et al., 2010a) used a circular grating chart surrounded by 12 LEDs as a glare source. While Stringham et.al. used two broadband white LEDs projected onto the screen (Stringham et al., 2011a). The visual angle between the observer and the light source in all the studies were ranging from 1° to 6° in order to measure the glare sensitivity in foveal and parafoveal regions. Most of the studies did not report the photometric quantities associated with the glare source, the ones who reported are mentioned in Table 2-1. Participants were exposed to the stimulus for an exposure time ranging from 2 minutes to 5 seconds in the studies. Participants either rated the glare on a linear 10-point scale with varying end labels or through a visual functioning questionnaire (Mangione et al., 1998) asking about eye strain on a category scale or performed a brightness adjustment task through which threshold was determined (cf. Table 2-1). A different study by Wilson (Wilson et al., 2021) did not use any glare stimulus but asked the participants to a set of questionnaires to assess their visual functioning (e.g. frequency of ocular comfort) in their regular lives and compared it with their measured MPOD values.

As stated before, all the studies, except Loughman et. al (Loughman et al., 2010a), found a significant influence of MPOD on glare sensitivity, we elaborate briefly on the key findings of all the studies. Stringham et.al (Stringham et al., 2011a) indicated that higher MP levels in the participants significantly improved their photostress recovery and visual performance in glare conditions. Another study from the same authors (Stringham et al., 2004a) showed that the participants with the broader spatial distribution of macular pigments (i.e. covering a greater range beyond fovea) had higher photophobia thresholds which were further confirmed by Wenzel et. al (Wenzel et al., 2006a). Hammond et al. showed a significant contribution of MP in protection against disability and discomfort glare (Hammond et al., 2013). A recent study by Wilson et al. showed that individuals with significantly higher MPOD levels experienced less eye pain or fatigue in their day-to-day activities assessed via questionnaires (Wilson et al., 2021). However, Loughman et al. concluded that the visual performance under glare conditions was unrelated to macular pigments. The authors discussed that the absence of a strong blue light component (absorbed by MP) in their white LED light source, might be the reason for their findings being different than the other studies. Although, a later study by Stringham et al. also used white LEDs with lesser blue content but still found that MP influenced glare sensation (Stringham et al., 2011a). None of the two studies reported the SPD of the light source, therefore, it is difficult to compare the findings. Given the significant findings demonstrated by many studies, macular pigments remain a promising factor that can potentially influence glare perception.

Few broader studies on the impact of macular pigment and oral carotenoids supplementation (lutein and zeaxanthin) on visual function indicate better visual performance after a period of supplementation (Kvansakul et al., 2006; Lien & Hammond, 2011a; Rodriguez-Carmona et al., 2006; Stringham, Bovier, Wong, & Hammond, Jr, 2010; Whitehead et al., 2006). Although they are out of the scope of the current thesis, these findings align with the glare reduction hypothesis of macular pigments.

This review concludes that macular pigment is a promising factor that has been known to influence discomfort glare in laboratory settings. Individuals with higher MPOD can tolerate glare which can partly explain the variability in glare perception. However, one important point to note is that the glare apparatus and assessment methods used in all these studies are very different from the ones used in evaluating visual comfort in indoor spaces. The glare conditions shown to the participants in the studies are by far not a realistic representation of any indoor space where glare is generally experienced, specifically the position of the glare source in the field of view. Therefore, these findings cannot be extrapolated to the glare conditions created by electric light or daylight in indoor spaces without further investigations. The research gap found by this review is:

Macular pigments in the retina have been found to influence glare sensitivity, but have only been studied in ophthalmological laboratory settings with the glare source close to the fovea. The influence of macular pigment on discomfort glare caused by daylight in daily indoor environments where the glare source is typically off-fovea is not known.

2.3 Color of light and discomfort glare

2.3.1 Cones, color vision and photopic luminosity function

This subsection briefly describes the cone photoreceptors, color vision and the functions quantifying photopic vision which are important to consider for delving further into color and discomfort glare interactions. The contents of this subsection, if not cited, are mainly based on two books: Human Perception and Performance (Boff & Lincoln, 1988), Sensation and Perception (Goldstein & Cacciamani, 2021).

Cones are one of the three known photoreceptors (the other two include rods and ipRGCs) in the human retina which are responsible for photopic and color vision. The photopic human vision state applies to the scenarios having luminance higher than 0.03cd/m2 that typically includes discomfort glare scenarios under daylight. On the other hand, scotopic (night) vision is mediated by the rod mechanism at luminance levels below this threshold. The mesopic range refers to the area where both mechanisms work together, and there is no sudden shift from one to the other. Figure 2-4 demonstrates the distribution of cones and rods in the retina. While the cones are concentrated within the fovea, rods are present at high density throughout most of the retina, with a sharp decline in the fovea. Three different types of cones differ in their sensitivity and are subdivided into short-wave sensitive (S), middle-wave sensitive (M) and long-wave sensitive (L) cones according to their absorption maxima (see figure 2-4). The number L cones are highest in the retina followed by M cones, while S cones are lowest in numbers.

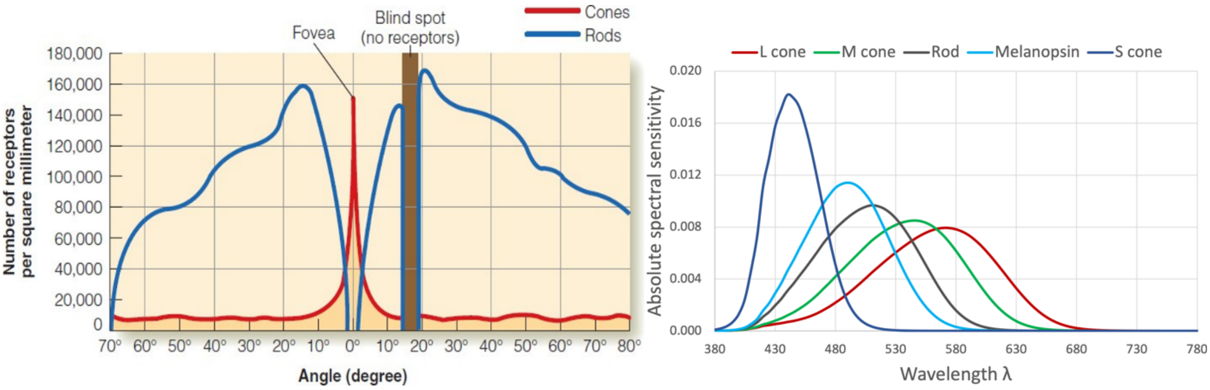


Figure 2-4 left: The distribution of rods and cones in the retina (Goldstein & Cacciamani, 2021). *Right: spectral sensitivity of the photoreceptors.*

Color vision is mediated by the cones, but the perceived color is not solely determined by wavelength; rather, it is dependent on the processing of wavelength information by the nervous system. The brain's construction of this perception of color is explained by two complementary theories: the trichromatic theory, which concerns photoreceptors, and the opponent-process theory, which is based on the concepts of antagonistic neurons. The trichromatic theory posits that color vision is made possible by the activity of three cone photoreceptors (L, M, and S cones) with different spectral sensitivities. When the light of a particular wavelength is encountered, it will stimulate these three cones in varying degrees, and the combination of the proportions of their activity will be associated with the perception of a certain color. Interestingly, physically different light sources (i.e., having different spectral power distributions) can be perceived as identical due to this phenomenon, which is known as metamerism. According to the opponent-process theory, human color perception is governed by three opposing systems: blue vs yellow, red vs green, and black vs white. The black vs white mechanism is the achromatic channel, which response positively to white light and negatively to the absence of light (as the result of the combined activity of L and M cones) and is responsible for luminance quantification. The red vs green mechanism responds positively to green and negatively to red (as the result of the addition of M cones and the subtraction of L cones). The blue vs yellow mechanism responds positively to yellow and negatively to blue (as the result of the addition of M and L cones, and the subtraction of S cones). Together, both theories are needed to fully explain the human color vision. The trichromatic theory explains how different types of cone receptors detect different wavelengths of light. Meanwhile, the opponent-process theory explains how the cones connect to nerve cells that ultimately determine how we perceive a color.

Light is electromagnetic radiation measured by radiometry. In order to characterize the light perceived by humans, photometric functions have been developed for more than 100 years. The Luminous efficiency or the spectral sensitivity of the human eye is characterized by the photopic luminous efficiency function ($V(\lambda)$). $V(\lambda)$ is the spectral weighting function that defines the relative visual effectiveness of light of different wavelengths (Stockman et al., 2008). It was first proposed by CIE in 1924 for 2° visual field ($V_{2^\circ}(\lambda)$ or simply $V(\lambda)$), which continues to be the basis of all the photometric measurements (Gibson & Tyndall, 1923). Since then, there have been several revisions to the $V_{2°}(\lambda)$ function, specifically to improve the sensitivity in the short-wavelength region (modification by Judd-Vos [33] [34] adapted by CIE 1988 as $V_M(\lambda)$ (CIE 086-1990, 1988)). The most recent one has been published by CIE TC 170-2 in 2015 (CIE 170-2: 2015, 2015), based on the physiologically derived cone-fundamentals by Sharpe and Stockman (Sharpe et al., 2005) as a linear function of L and M cones. Moreover, it has become well known that the spectral sensitivity of the human eye changes from the fovea towards the perifovea of the retina, which is attributed to the presence of blue-light filtering macular pigments in the macula (Stiles & Burch, 1959). Following these results, CIE established photopic spectral sensitivity function CIE $V_{10°}(\lambda)$ for parafoveal light sources up to 10-degree visual field (CIE publication 165:2005, 2005). Studies have indicated that the ratio $V_{2°}(\lambda)$ / $V_{10°}(\lambda)$ results in a function which is characteristic of the absorption spectrum by the macula (Adrian, 2003).

Typical methods to derive $V(\lambda)$ include side-by-side matching task or flicker photometry to determine relative brightness perception at the different wavelengths of the visible spectrum under constant and neutral (achromatic) adaptation (Gibson & Tyndall, 1923; Vos, 1978). $V(\lambda)$ has a utility over a range of practical visual tasks for characterising luminous stimulus as reviewed by Lennie et al. (Lennie et al., 1993). However, several previous research has shown that the $V(\lambda)$ function has limited applicability in conditions that fall outside those in which the function has been developed, whether these "new" conditions are: conditions involving chromatic and colored background adaptation (Eisner, 1982; Stockman et al., 2008; Swanson, 1993), conditions including large-sized stimuli (Kuyk, 1982), stimuli which are off-axis (Adrian, 2003) or long duration stimuli with short wavelength targets [38] or even age-related reduction in efficiency (Sagawa & Takahashi, 2001). These points are specifically interesting for this thesis since we are interested in evaluating the influence of glare from colored daylight which would include conditions with non-neutral chromatic sources, large field, off-axis and longer duration stimuli, which therefore all represent conditions where the classical $V(\lambda)$ falls short in predicting luminance.

2.3.2 Studies on the influence of color of light on discomfort glare

Table 2-2 summarizes the studies evaluating the influence of color of light on discomfort glare perception. In all the studies, color of light have found to influence discomfort glare perception and higher discomfort was observed in blue-colored light compared to any other colored light. It can be seen from the table that all the studies up to now are conducted with electric light as a glare source, there are no studies evaluating the color of daylight.

The influence of color of light on discomfort glare has been studied many times in transportation research in the context of the colored headlamps of vehicles and the glare experienced by drivers. Flannagan et. al (Flannagan et al., 1989b) evaluated the glare response from 16 subjects for monochromatic light sources of equal illuminance at six wavelengths on a 9-point De Boer scale in a mock-up driving scenario and showed that the lowest glare perception was at 577nm stimulus (green light), followed by 650nm (red light) and highest at 480nm (blue light). Another study by the same authors compared the High-intensity discharge (HID) lamps that have higher blue light content with the yellowish Tungsten-Halogen lamps and found the HID to induce higher estimates of discomfort glare (Flannagan, 1999b). Similar results were demonstrated by Sivak et. al (Sivak et al., 2005), where the discomfort glare ratings were linearly related to the amount of blue content in LEDs as weighted by the S-cone sensitivity function. Bullough (Bullough, 2009) published experiments where participants evaluated glare from near-monochromatic light sources from 450nm to 700nm at 5° and 10° viewing angles, and found consistent results of higher glare perception at shorter wavelengths. Authors also found that the glare sensitivity at 10°was higher in the short-wavelength range compared to 5° owing to the decline of blue-light filtering macular pigments at 10°. Based on this finding, authors also proposed a new $V(\lambda)$ function for discomfort glare shown in equation 2-1 as $V_{DG1}(\lambda)$ to replace the CIE $V(\lambda)$, hypothesizing that S-cone response has a higher contribution in discomfort glare mechanism. However, this model failed to predict the data from Fekete et. al (Fekete et al., 2010) even though they also found that shorter wavelengths created higher discomfort. Therefore, the authors proposed another model based on their findings that model includes the contribution of two chromatic channels (L-M and the (L+M)-S cone inputs) and the achromatic channel (L+M), as shown in equation 2-2. Kimura-Minoda and Ayama (Kimura-Minoda & Ayama, 2010), on the other hand, tested six colored LEDs from 459nm to 620nm of two red, green, blue, amber, and white color and a tungsten-halogen bulb and found that blue LED caused the most discomfort while the other LEDs produced a similarly lower discomfort. Based on their findings, they proposed another luminous efficiency function shown in equation 2-3 that consider the spectral sensitivities of the red-green and yellow-blue opponent chromatic channels. It should be noted that all the proposed functions have found different coefficient values for 2° and 10° viewing angles.

$$V_{DG1}(\lambda) = V_{10^\circ}(\lambda) + kS_{10^\circ}(\lambda) \tag{2-1}$$

$$V_{DG2}(\lambda) = aV'(\lambda) + b[1.62L(\lambda) + M(\lambda)] + c[L(\lambda) - M(\lambda)] + e[1.62L(\lambda) + M(\lambda) - S(\lambda)] \tag{2-2}$$

$$V_{DG3}(\lambda) = V(\lambda) + a'(L(\lambda) - 1.235M(\lambda) + 0.182S(\lambda)) + b'(L(\lambda) + M(\lambda) - 5.835S(\lambda)) \tag{2-3}$$

A comprehensive review and assessment of these different photopic luminous efficiency functions have been conducted by Yang et al. (Yang et al., 2018). The authors have shown that the glare metrics based on any of these functions can better account for the effect of color on glare perception and work better in comparison to the Unified Glare Rating (UGR) metric (that is based on V(λ)). Figure 2-5 plots these functions across the visible range and compare them to the CIE $V_{2^\circ}(\lambda)$ and $V_{10^\circ}(\lambda)$ functions. It can be observed from the figure that all of these functions have higher variances in spectral sensitivities under shorter wavelength regions compared to longer wavelength regions.

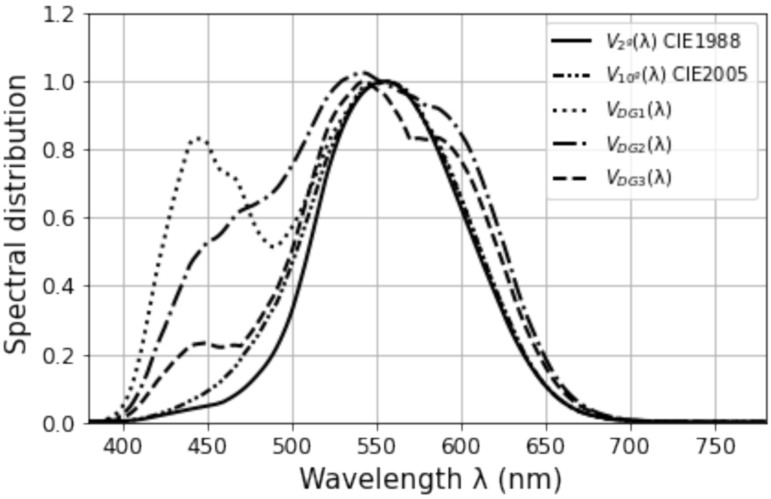


Figure 2-5 Comparison of proposed discomfort glare sensitivity functions with CIE $V_{2^\circ}(\lambda)$ and $V_{10^\circ}(\lambda)$ functions

Later studies demonstrated the effect of color of light beyond the automobile context and rather in indoor spaces with overhead lighting of blueish and yellowish colors and found consistent results of experiencing glare more often in blueish light sources (Wei et al., 2014; Zhang et al., 2013). Sweater-Hickcox et al. demonstrated that changing the color of the background light source while keeping the color of the glare source as white, still has a similar effect of experiencing higher discomfort in blue colored background light source (Sweater-Hickcox et al., 2013). The studies that evaluated the CCT of the glare sources instead of SPD again found similar results of experiencing higher discomfort in light sources with higher CCTs (bluish) than lower CCTs (yellowish) (P.-L. Chen et al., 2015; Suzuki et al., 2019). Except one study by S. Choi & Ko that did not find a significant difference in glare perception between overhead lighting scenarios of 2700K and 6000K, although the calculated UGR values were slightly different between the two CCT scenarios indicating the difference in lighting conditions that could have been the reason of glare perception.

Table 2-2 Review of literature on the influence of color, SPD and CCT of light on discomfort glare

Study	Sample size	Type of luminaire	Tested light sources' color/dominant wavelength/CCT	Angle between source & observer	Glare assessment method	Key Results
(Suzuki et al., 2019)	23	LCD screen	Black, blue, cyan, green, yellow, red, magenta	4.62°	Pupil size, side by side luminance matching	Blue was rated as brightest condition. Blue hues constricted pupil more than other hues
(Niedling & Völker, 2018)	36	LED	3700K, 3400K, 6500K, (having same Ev)	4° vertical	9-pt category scale	LED with 6500K CCT showed higher glare ratings than all other LEDs
(S. Choi & Ko, 2018)	33	LED	2700K, 3000K, 4000K, 5000K, 6000K	overhead	7-pt category scale	No difference in glare perception
(Yang et al., 2016)	20	LED	Blue1-435 nm, Blue2-455 nm, Blue3-477 nm, Green-527 nm, Red-623 nm, White-4200 K	0°, 20°	7-pt category scale	Blue (B1>B2>B3) LED was most discomforting, then red, green and white LEDs
(P.-L. Chen et al., 2015)	8	LED	3100K, 4000K, 5300K	0°, 10°	De boer 9-pt scale	Higher CCT caused higher discomfort
(Wei et al., 2014)	26	Fluorescent lighting	5000K, 3500K	overhead	7-pt agreement scale	Higher CCT caused higher discomfort
(Zhang et al., 2013)	18	Fluorescent lighting	4000K, 6300K	overhead	7-pt category scale	Higher CCT caused higher discomfort
(Sweater-Hickcox et al., 2012)	10	LED	Glare source: White LED (6500k), Background1: Yellow LED (Green-525nm+ Red-635nm), Background2: Blue-465nm	2°	De boer 9-pt scale	Blue background LEDs were rated more glary than yellow or white
(Kimura-Minoda & Ayama, 2010)	15	LED, tungsten-halogen	Red1-628nm, Red2-620nm, Green-542nm, Blue-459nm, Amber-586nm, Red tungsten-halogen bulb-617nm, White-6800K	2°, 10°	De boer 9-pt scale	Blue had highest glare perception. No significant difference among other stimuli. Brightness and glare perception were correlated
(Fekete et al., 2009)	10	Xenon lamp	420nm-630nm at 10nm steps	2°, 10°	De boer 9-pt scale	Higher discomfort under shorter wavelength
(Bullough, 2009)	24	Xenon lamp	450, 510, 590, 650 and 700 nm	5°, 10°	De boer 9-pt scale	Higher discomfort under shorter wavelength
(Sivak, 2005)	12	LED	4000K, 4800K, 6600 K	0.5°	De boer 9-pt scale	Discomfort glare was linearly related to amount of blue content in LED
(Bullough et al., 2004)	31	HID, halogen, blue-filtered halogen lamp	450nm, 510nm, 590nm, 650nm, 700 nm, 420nm, 450nm, 490nm, 577nm	5°, 10°	De boer 9-pt scale	Higher discomfort under shorter wavelength. V(λ) does not accurately characterize discomfort glare.
(Flannagan, 1999b)	12	Tungsten-halogen (TH) and HID	HID: blue-white, TH: yellow	0.3°, 0.6°	Linear glare scale	SPD affected glare perception, HID were more discomforting than TH lamps
(Berman et al., 1995)	12	Fluorescent lighting	Cool-white, greenish blue-505nm	24°x33°	Visual analog scale (0 to 100mm)	Scotopically enhanced light source caused lower level of discomfort
(Flannagan et al., 1989a)	16	Monochromatic lamps	480nm, 505nm, 550nm, 577nm, 600nm, 650nm	7°	De boer 9-pt scale	Highest discomfort at 480nm > 505nm > 650nm > 600nm > 550nm > 577nm (most comfortable)

Although there are no studies on the influence of color of daylight on discomfort glare, some of the studies have investigated the effect of filtered daylight by colored façade on visual quality, preference, and acceptance. Two recent studies by Liang et. al (Liang et al., 2018, 2021) on artificial colored windows with 31 subjects found that bronze glazing had higher acceptance than blue glazing, even though the visual performance was lower in bronze glazing compared to blue glazing. Another study conducted in Beijing with 11 subjects reported that blue, clear and bronze glazing were rated more visually comfortable than green, dark blue and red glazing (X. Chen et al., 2019). 36 Participants preferred daylight filtered through bronze glazing compared to blue and neutral glazing in a scale model (Arsenault et al., 2012).

A study by Chinazzo et al. (Chinazzo et al., 2018) found that participants were more visually comfortable under color-neutral glazing compared to blue and orange-colored glazing. Overall, warmer or neutral-colored daylit environments were quite consistently found to be more visually acceptable, in these various studies, than the cooler colored environments, which, by extension, can provide some prospective insights on discomfort glare perception.

Since the SPD and the CCT of daylight can vary with the type of glazing, as well as the weather and time of the day, it is worth studying the influence of these parameters on discomfort glare perception in the context of daylit indoor spaces. Furthermore, the increasing use of blue-tinted EC glazing and colored photovoltaic glass that causes spectral shifts in filtered daylight due to their spectrally selective transmittance, might have an influence on discomfort glare perception. Therefore, there is a need to investigate the impact of colored daylight as a usage of colored glass façade on discomfort glare. The research gap found by this review is:

The color of electric lighting has been shown to influence discomfort glare, but the influence of color of daylight on discomfort glare is not yet known.

2.4 Summary of research gaps and emerging questions

The literature review supports the hypothesis that discomfort glare predictions can be improved by including relevant factors influencing discomfort glare. The identified gaps in the literature are as follows:

- Macular pigments in the retina have been found to influence glare sensitivity but have only been studied in ophthalmological laboratory settings where the glare source was located close to the fovea. The influence of macular pigments on discomfort glare caused by daylight in normal indoor daylit spaces where the glare source is located off-fovea is not known.

- The color of electric lighting has been shown to influence discomfort glare, but the influence of color of daylight on discomfort glare is not yet known.

- There exist potential pitfalls concerning the design of experiments, the use of glare rating scales and the confounding factors related to the state of the observer and the environment. To achieve reliable results, these potential biases should be minimized in the methodology.

Consequently, the following research questions will be studied in this thesis to fill the gaps:

- Whether the macular pigment density has an influence on the perception of discomfort glare and the nature of this influence is

- Whether the color of daylight has an influence on discomfort glare perception and what the nature of this influence is.

These research questions are further elaborated in the next chapter. To fill the gap regarding the design of the experiments, this thesis will implement countermeasures to account for the potential biases that are further detailed in our research approach in section 3.3.

Chapter 3

Research scope and structure

3.1 Problem Statement

As we could see from the breadth of bibliographic references that form the State of the Art discussed in the previous chapter, the complex and multidisciplinary nature of the glare phenomenon. To answer the questions on *why there exists large inter-individual variability in glare perception* or *what is the physiological mechanism behind discomfort glare* or *what is the role of the color of the light source in experiencing glare* requires the involvement of a large range of disciplinary fields, from ophthalmology and photometry to psychophysics and neuroscience. These fields tend to remain quite disconnected from one another, which probably explains in part the slow progress that has been made so far in understanding the discomfort glare phenomenon (Loe, 2016; Mainster & Turner, 2012). It is, therefore, necessary to incorporate an interdisciplinary approach to anticipate what creates or influences the perception of discomfort glare from daylight.

Towards this end, and to specifically address the existing limitations of the discomfort glare metrics described in Chapter 1 (section 1.3), we hypothesize in this thesis that discomfort glare models can be improved by including new factors in these models likely to influence glare perception. In particular, the conducted literature review has revealed two very promising factors that should be further evaluated: the density of macular pigments in the human eye and the color of daylight. In other words, the goal of this thesis is:

To determine the influence of macular pigment density and of color of daylight on discomfort glare from daylight.

By means of user studies conducted in controlled laboratory settings with daylight as the only source of light and the sun as the glare source, we will determine the influence of these two factors on discomfort glare. As pointed out earlier in section 2.1.3 and will be discussed in detail for each experiment (cf. Chapters 4, 5,6,7 and 8), special attention has been paid to the design of these user studies to minimize potential biases from confounding factors.

3.2 Research questions and objectives

As discussed in section 2.4, the two main research questions, and associated research objectives and approach to answer them, can be expressed as follows:

Research question 1:

What is the influence of macular pigments on discomfort glare from electric light and daylight?

This question is answered by:

By conducting a pilot user study with electric light as the glare source, to develop a methodological approach to evaluate subjective individual glare sensitivity thresholds based on which participants could be then grouped into less sensitive and more sensitive groups. These two groups were then compared in terms of their measured MPOD values. This part is covered in Chapter 4.

By conducting a user study in daylight to determine the influence of macular pigment on discomfort glare from daylight- measuring the MPOD and comparing it to the glare evaluations done under daylit space with color-neutral glazing as well as blue-tinted glazing, given the known properties of macular pigment to attenuate blue light. This part is covered in Chapter 5.

Research question 2:

Does the color of daylight (i.e. sun disc filtered by a colored glazing) have an influence on discomfort glare perception and what is the nature of this influence?

This question is answered by:

By first conducting a user study under blue electrochromic glazing with an aim to establish an experiment protocol that counters potential experimental design biases (cf. Table 3-1), to determine the performance of discomfort glare models in predicting user's glare perception when the sun is in the field of view as a glare source, to determine participants' glare perception under blue EC glazing which causes a spectral shift in the daylight and changes its color. This part is covered in Chapter 6.

Then by determining whether there is a difference between glare perception from the colored sun disc as a glare source, resulting from using the blue EC glazing compared to the color-neutral glazing as proof of concept to answer the core research question. And by determining whether any previously proposed discomfort glare spectral sensitivity functions can explain the effect of color, if found, under daylight. This part is covered in Chapter 7.

Finally, by conducting a user study to determine whether the sun disc filtered by colored glazing (blue, green, red vs neutral) influences discomfort glare perception. This part is covered in Chapter 8.

3.3 Research approach

As explained by Goldstein & Cacciamani, once a perceptual phenomenon has been defined, two approaches can be used to study it experimentally (Goldstein & Cacciamani, 2021):

- The psychophysiological approach involves measuring the relationship between stimuli and physiological processes on the one hand, and between the physiological processes and perception on the other (Stern et al., 2001).
- The psychophysical approach, introduced by Fencher (fencher, 1966), consists of the use of methods to measure the relationship between stimuli and perception (e.g., ask an observer if they perceive glare from a light stimulus).

In this thesis, we will follow both approaches: a psychophysiological approach to determine the influence of macular pigment density (physiological factor) on discomfort glare (perception) and a psychophysical approach to determine the influence of color of daylight (physical stimuli) on discomfort glare (perception).

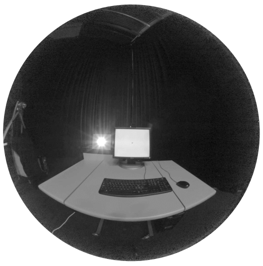
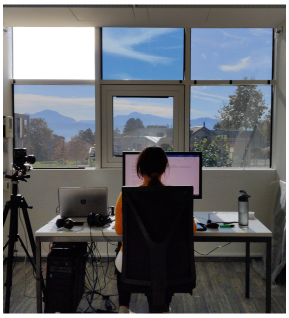
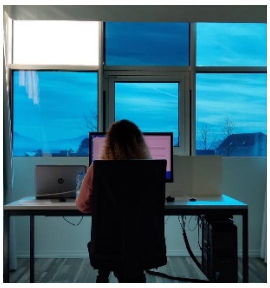
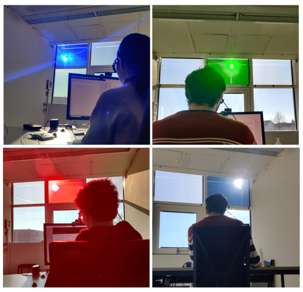
To fulfil the objectives described in the previous section, we designed three user studies with dedicated attention to minimizing the potential biases referred to in section 2.1.3: Table 3-1 summarizes the possible caveats based on the reviewed literature and describes the countermeasures adapted in the methodology to overcome the biases.

The three mentioned user studies were conducted during three consecutive winter periods (2019-2022) in Lausanne, Switzerland over the span of four years that involved total 131 human participants. The studies, their objectives and the way in which they are structured in chapters in this thesis are detailed in Table 3-2.

Table 3-1 Possible caveats in experimental design and countermeasures implemented in the research methodology of this thesis

Possible caveats in experimental design **(Based on past studies mentioned in section 2.1)**	**Countermeasures implemented in methodology**
Uncertainty in the understanding of terms evaluated in experiments by the subjects	Verbal and written descriptions of the assessed terms were provided to the participants.
Potential bias in the use of rating scales and unreliability in subjective assessments	Several glare questionnaires (designed to best minimize the potential biases) were asked in the survey and internal consistency between the questions was evaluated (cf. Appendix A1: Comfort questionnaires; A3: additional publication on comparison of glare questions).
Potential anchor point bias in luminance settings	Participants were exposed to the experimental conditions in random order.
Potential influence of chronotype of participants	Volunteers with extreme chronotypes, evaluated by (Horne & Östberg, 1976), were not shortlisted to participate (cf. Appendix A1: pre-selection questionnaires).
Potential influence of time of the day	Experiments were conducted for a fixed duration of two hours between 9.30 to 14:30 to minimize the variability in time of day between participants.
Potential influence of season	Experiments were conducted only during the winter season (Nov -Feb) for all the participants.
Potential influence of task difficulty	Typing task given to participants was evaluated beforehand to have the same level of difficulty.
Potential influence of previous light exposure before the experiment	A pre-test phase under electric light followed by a dark adaptation period (total 20-30 mins) was maintained for all the participants.
Potential influence of the emotional and physical state of the participant	Participants were asked to report their emotional and physical health conditions at the start of the experiment and if not feeling well, the researcher was called upon to cancel the experiment immediately (cf. Appendix A1: Background questionnaires).
Potential influence of caffeine ingestion	Participants were not allowed to drink or eat anything, except water, during the experiment. They were also asked to report the number of coffee cups they had before the experiment (cf. Appendix A1: Background questionnaires).
Potential influence of fatigue on assessment while exposed to the experimental condition	Only four experiment conditions (15-20mins each) were shown to every participant, followed by a break aimed at maintaining a balance between the minimum required exposure time and the maximum time a subject can spend without getting tired.

Table 3-2 User studies conducted under the scope of the thesis with their specific objectives and chapters in the thesis.

No.	User study	Objectives of study	Thesis chapters based on the user study
1a.	Electric light (N=55) 	To determine the influence of macular pigment optical density on sensitivity to glare from an electric light source	Chapter 4: Sensitivity to glare from electric light and relationship with macular pigment optical density
1b.	Color-neutral glazing (N=55) 	To determine whether there is a difference between the glare perception in blue EC glazing compared to neutral glazing To determine the influence of macular pigment on discomfort glare from daylight under color-neutral and blue-tinted glazings	Chapter 5: Influence of macular pigment density on the sensitivity to discomfort glare from daylight Chapter 7: Perceived glare from the sun behind tinted glazing: comparing blue vs. color-neutral tints
2	Electrochromic glazing (N=20) 	To establish the experimental design that counters potential experimental design biases To evaluate the performance of EC glazing in minimizing discomfort glare and the reliability of glare metrics scenarios including the sun in the FOV	Chapter 6: Behind electrochromic glazing: Assessing user's perception of glare from the sun in a controlled environment Chapter 7: Perceived glare from the sun behind tinted glazing: comparing blue vs. color-neutral tints
3	Colored glazing (red, green, blue and neutral) (N=56) 	To determine whether the sun disc filtered through saturated colored glazing (blue, green, red) create different level of discomfort glare from the sun	Chapter 5: Influence of macular pigment density on the sensitivity to discomfort glare from daylight Chapter 8: Influence of color of daylight filtered by colored glazing on discomfort glare

3.4 Thesis layout

This thesis comprises nine chapters and is organized into four parts. The first and last parts serve as the introduction and conclusion, respectively, while the middle two parts address the two primary research questions of the thesis outlined in section 3.2. Aside from the four chapters in the introduction and conclusion sections, the other five chapters consist of papers written for publication in peer-reviewed journals and conference proceedings. To date, three papers have been published (one in conference proceedings and two in peer-reviewed journals), and the remaining two have been submitted to two peer-reviewed journals. All the co-authors of the papers are listed, and their consent was obtained.

The contents of the thesis have been organized as follows:

Part I: Introduction

Chapter 1 (Research context) introduced the context of the research and the motivation of the thesis. A brief introduction of discomfort glare and prediction models was provided which also discussed the current limitations and lesser-known aspects of the discomfort glare. The overall goals of the thesis emerging from the limitations were then introduced.

Chapter 2 (State of the art) presented a review of the existing literature on the potential factors influencing discomfort glare which have not yet been included in the current glare models. From this review, we identified two promising factors that are most likely to influence glare and summarized the current knowledge available about them from the literature, which led us to the research gaps that this thesis aims to fill.

Chapter 3 (Research scope and structure) summarized the research objectives and the overall adopted approach and provides the structure that the rest of the thesis will follow.

Part II: Macular pigment and discomfort glare

This part addresses the first of the two main objectives of this thesis which is to determine the influence of macular pigment on discomfort glare.

Chapter 4 (Sensitivity to glare from electric light and relationship with macular pigment optical density) is based on the first experimental study (No.1a in Table 3-1). It presents a user study conducted with electric light as the only glare source that aimed to determine the influence of the participants' macular pigment optical density on their sensitivity to glare. The contents of this chapter were published with a slightly different title (*On sensitivity to glare and its relationship with macular pigment optical density*) in the Proceedings of the CIE 2021 conference (S. Jain, J. Wienold, M. Andersen 2021).

Chapter 5 (Influence of macular pigment on the sensitivity to discomfort glare from daylight) is based on the outcomes of both the first and third experimental studies (No.1b and 3 in Table 3-1): these two user studies were both conducted under daylight with either a color-neutral glazing (experiment No. 1b) or a blue colored glazing (one of the four glazing types used in experiment No. 3) and both included ocular characteristics measurements. More specifically, this chapter investigates the influence of ocular characteristics on discomfort glare by comparing the measured MPOD, retinal thickness and photostress recovery time for each of the participants with their reported discomfort glare ratings under blue and color-neutral glazing. The contents of this chapter are prepared to be submitted under the same title to the *Scientific Reports* journal from the *Nature* publishing group (S. Jain, J. Wienold, S. Gisselbaek, C. Eandi, A. Kawasaki, M. Andersen).

Part III: Color of daylight and discomfort glare

This part addresses the second of the two main objectives of this thesis which is to determine the influence of color of daylight on discomfort glare.

Chapter 6 (Behind electrochromic glazing: Assessing user's perception of glare from the sun in a controlled environment) is based on the second experimental study (No.2 in Table 3-1). It presents a user study conducted in a test room with EC glazing aimed at determining the performance of EC glazing in controlling glare when the sun is in the observer's FOV and the performance of glare metrics in predicting discomfort under such conditions. This study also acts as a pilot for setting up a robust experimental protocol that would minimize potential biases and restrict confounding variables, which also inspired the protocols of the next two user studies conducted under the scope of this thesis (No. 2 & 3 in Table 3-1). The contents of this chapter have been published under the same title in the *Energy and Buildings* journal (S. Jain, C. Karmann, J. Wienold 2021).

Chapter 7 (Perceived glare from the sun behind tinted glazing: comparing blue vs. color-neutral tints) is based on the same experimental study as Chapter 6 (No. 2) but also on the first experimental study (No.1b in Table 3-1), this time from the perspective of comparing blue EC glazing to color-neutral glazing in terms of discomfort glare perception. We implemented four V(λ) modifications, suggested by past studies, to include the effect of color in glare models and compared them. The comparison between the glare perception from the color of daylight filtered by blue vs. color-neutral glazing act as a proof of concept on whether an influence of color on discomfort glare exists. The contents of this chapter are published under the same title for the *Building and Environment* journal (S. Jain, J. Wienold, M. Lagier, A. Schüler, M. Andersen 2023).

Chapter 8 (Influence of color of daylight filtered by colored glazing on discomfort glare) is, like Chapter 5, based on the third experimental study (No.3 in Table 3-1) but this time focusing on comparing the four different types of colored glazing to one another (neutral, blue, green and red), intending to determine whether there is an influence of the color of sun disc (filtered by the glazing) on the participants' glare perception. The contents of this chapter are prepared for submission under the same title to the *Leukos* journal (S. Jain, J. Wienold, M. Andersen).

Part IV: Conclusion

Chapter 9 (Conclusions) concludes the thesis by summarizing the key findings and novel contributions. It also provides the implications that these results can have on visual comfort research and more broadly on the building industry. The chapter ends with some suggestions for future works and broader outlook.

PART II: MACULAR PIGMENT & DISCOMFORT GLARE

Chapter 4

Sensitivity to glare from electric light and its relationship with macular pigment optical density

Objectives

The objectives of the study presented in this chapter are:

1. To establish a methodology for determining the glare sensitivity of the test participants from a dimmable electric.

2. To determine the influence of macular pigment optical density on the evaluated sensitivity to glare from electric light.

On sensitivity to glare and its relationship with macular pigment

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Abstract

Current trends in discomfort glare research have suggested the influence of physiological parameters on individual glare perception. To this end, we hypothesize that a specific ocular physiology characteristic, namely the macular pigment (MP) in the retina, could have an influence on glare sensitivity, encouraged by recent findings from the literature that have shown that high MP levels were indicative of better visual performance. This study investigates whether a person's sensitivity to glare could be somehow correlated to their macular pigment optical density (MPOD). We measured MPOD in 56 participants and compared it with their discomfort glare thresholds, which were determined psychophysically by exposing the participants to a series of lighting conditions varying in intensity. We found that the influence of MPOD on glare sensitivity is borderline significant with small effect size but does not follow intuition. Additional data will be required to validate and refine these initial findings.

Keywords: *Glare, Macular pigment, User assessment, Sensitivity*

4.1 Introduction and state of the art

Properly addressing glare risks in buildings is crucial towards achieving comfortable visual environments. It is, therefore, necessary to understand what causes or influences the perception of discomfort glare. Although several glare prediction models based on physical quantities have been developed in the last two decades, current models are unable to capture the large inter-individual variability that is observed in the perception of discomfort glare (Eble-Hankins & Waters, 2005b). If we assume that the tolerance towards discomfort glare does indeed vary among individuals, it seems plausible that certain eye morphology parameters could at least in part explain this variability.

Previous studies have shown the influence of macular pigment on the visual performance in the presence of glare (Lien & Hammond, 2011b; Stringham, Bovier, Wong, & Hammond, Jr, 2010; Stringham et al., 2011b; Wenzel et al., 2006b). The yellow macular pigments, mainly comprised of carotenoids (lutein, zeaxanthin, and meso-zeaxanthin), are deposited in the fovea in the Henle fibre layer, in the parafovea and in the inner plexiform layers of the retina. Macular pigment covers about 6.7° in the horizontal and 3.0° in the vertical directions of the central retina (Bernstein et al., 2010). Several techniques are available to measure macular pigment that mainly include either physical methods (such as Fundus autofluorescence imaging (Delori et al., 2001)) or psychophysical methods (such as heterochromatic flicker photometry (HFP) (van der Veen et al., 2009b)). In visual comfort research, psychophysical methods, mainly HFP, is used more often to measure macular pigment optical density (MPOD). MPOD is a measurement of the attenuation of blue light by macular pigment and is linearly related to the amount of lutein and zeaxanthin in the macula (Bernstein et al., 2010).

A study by Stringham et.al (Stringham et al., 2004b) indicates that a high MPOD level protects the retina as the macular pigments absorb high-energy short-wavelength light. Another study from the same author showed that subjects with broader MPOD spatial distribution would perceive less discomfort glare (Stringham et al., 2011b). It was hypothesized from this study that the subjects with relatively high macular pigment density tolerate more intense light. A study by Lien et al. (Lien & Hammond, 2011b) also indicated that the absorption of short wavelength light by the macular pigment reduces the discomfort glare. However, another study from Loughman et al. (Loughman et al., 2010b) concluded that visual performance under glare conditions were unrelated to macular pigment. The lack of consistency between these findings suggests a need for more research in this area.

To address this need, the present study discusses preliminary results from a test room experiment conducted with 56 human participants to evaluate the glare sensitivity among the participants and its relationship with macular pigment density measured using psychophysical methods.

4.2 Method

A total of 56 young healthy individuals between 18 and 35 years of age participated in the study. The requirements for selection were to be in healthy conditions, have a normal color vision, no other visual impairment, have a BMI between normal ranges, must have English proficiency level C1 or higher, must not use drugs and must not abuse of alcohol. Experiments were conducted at EPFL campus in Lausanne, Switzerland in a controlled test room environment with no daylight access in which the thermal and visual parameters of the room were monitored. The experiments were approved by the EPFL Human Research Ethics Committee (No. 065-2019).

4.3 Experimental design and setup

4.3.1 Measurement of visual characteristics

We measured the best corrected visual acuity and contrast sensitivity of each participant monocularly to collect baseline ocular data and ensure normal vision. These tests were performed on a validated computer software FrACT 3.10.5 (Bach, 1996b) at a distance of 170cms from the computer screen. Calibration settings were adapted as per user's computer screen resolution and the distance between user's eyes and the screen were set to allow the measure of the maximal acuity.

Macular pigment optical density (MPOD) was measured using a macular pigment screener device, QuantifEye MPS II, that uses the heterochromatic flicker photometry method to provide an estimate of the blue light absorption of MP. MPOD values are measured on a scale of 0 to 1, where a lower value indicates a higher level of blue light hitting the macula. In this test, participants viewed a centrally fixated target and made flicker matches at two light wavelengths of 465nm (blue light) which is absorbed by the MP and another of 530nm (green light), not absorbed by MP. Flicker matches were made in the foveal region of the retina. These measurements were done under electric lighting.

4.3.2 Glare sensitivity test setup

Participants' sensitivity to glare was evaluated experimentally in that they were asked to rate glare from a dimmable electric light with predefined levels of luminance that the participants were exposed to in their near foveal field of view. The LED glare source was of diameter 10cm, CCT of 4800K with a diffuser sheet, and the angle between the glare source and the participant's line of sight was 20°. Note that the glare source was the only light source in the test room during the glare assessment session. Participants were exposed to 5 light levels that differed in glare stimuli luminance ranging from 265363 cd/m2 (UGR = 36) to 2000 cd/m2 (UGR = 8) designed to cover the glare sensation spectrum from imperceptible (UGR < 10) to intolerable glare (UGR > 34) as shown in Table *4-1*. The naming convention followed for the scenes shown to the participants is based on the percentage of lighting intensity of the LED. These five light levels are illustrated in Figure *4-1* as false color images and the glare scores and luminance values associated with them are provided in Table *4-1*.

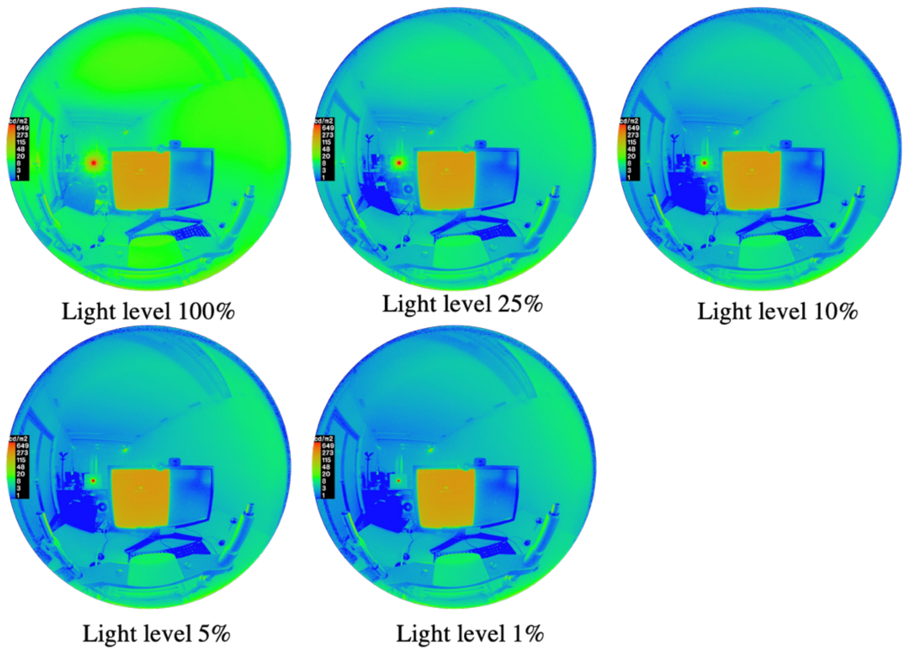


Figure 4-1 HDR false color images of the experimental scenarios shown to participants.

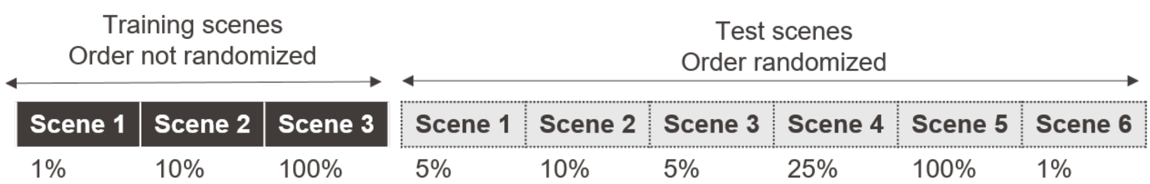


Figure 4-2 Experimental scenes shown to the participants.

Table 4-1 Description of the visual properties of the five experimental conditions

Scene	UGR	Source Luminance (cd/m2)	CGI	Subjective Categorization (as per (Carlucci et al., 2015)
1%	9	2019	5	Imperceptible
5%	15	12037	18	Perceptible
10%	20	25686	22	Unacceptable
25%	26	66051	29	Uncomfortable
100%	35	265636	37	Intolerable

As illustrated in Figure *4-2* , each participant was exposed to a sequence of nine visual scenes in total, reordering and sometimes repeating the five light scenarios described above as follows: the first three scenes, which varied from lowest (1%), middle (10%) and highest (100%) light intensity, were the training scenes and were thus not randomized between the participant to avoid anchor bias (Fotios, 2009); the remaining six visual scenes consisted of the five testing scenes considered in the analysis and were thus randomized to avoid order bias and included one repeated condition to check the consistency of the evaluation done by the participant. One sequence is shown as an example in Figure 4-2. To further check the reliability of the test and consistency of the participants, a post-trial session was then conducted where participants were exposed to continuously increasing intensity of the LED until they reported visual discomfort and the intensity value was recorded.

4.3.3 Experimental procedure and questionnaires

The experimental procedure lasted for 30 minutes with one participant at a time and was sequenced according to the timeline shown in Figure 4-3. For each session, participants were first introduced to the experiment and invited to sign the consent form. They then completed a background questionnaire which allowed to collect their baseline data: questions were about their age, gender, eye color, their current mood, feelings and physical state, and their sensitivity 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.

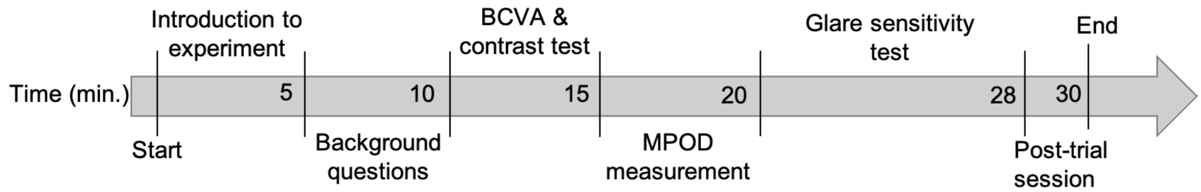


Figure 4-3 Experiment timeline

After completing the background survey, participants performed a visual acuity and contrast test on computer screen. Then, the MPOD for participant's left and right eye were measured using the MPSII screener device. Afterwards, the glare sensitivity test was conducted in the setup described in section 4.3.2. Participants performed the test with their chin fixed on a chin rest to keep their head in a constant position with respect to the computer screen and the glare source. During this test, the participants kept their focus on the screen, while the glare source was at 20° horizontal and 0° vertical from their central line of the sight and visible in their parafoveal field of view. Participants answered question 1 and 2 shown in Table 4-2 at the start of the test. Then, they were shown 9 scenes of varying glare source intensities as described in section 4.3.2. During the exposure to each scene for 20 seconds, participants read the text shown on the screen. After 20 seconds, they were asked to rate the discomfort from glare on a binary Yes/No scale and on a 6-point Likert scale listed in Table 4-2 as questions 3 and 4 respectively. We chose two glare scales to compare the responses and ensure consistency in within-subject responses. We selected a 6-pt scale to represent all the glare levels and avoid ambiguity created by a neutral middle point in an odd number scale. At the end of the procedure, the post-trial session was conducted where participants reported the threshold intensity causing discomfort from the glare.

Table 4-2 Questionnaires asked during glare sensitivity test

Survey questions	Response scale
Are you sensitive to bright light in general?	Yes – No – I don't know
Please rate your sensitivity to bright light:	Not sensitive 0-1-2-3-4-5-6-7-8-9-10 Very sensitive
Do you feel any discomfort due to glare at the moment?	Yes – No
How much discomfort are you experiencing from the glare at the moment?	Not at all – Slight – Moderate – Strong – Very Strong – Extreme

4.3.4 Data cleansing and statistical methods

Data collected was checked thoroughly to ensure consistency in within-subject responses. For any participant, if the difference in glare rating on the 6-point scale was more than 1-point for the repeated light intensity, then the session was removed from the final analysis (which happened for 3 participants). Descriptive analysis was performed to compare the subjective responses to the varying luminance of the glare source reported on the binary and the 6-pt scale. We used Spearman's rank correlation to compare the glare source luminance with the subjective responses reported on the 6-pt scale.

We derived a glare threshold for each participant from their subjective responses reported during the glare sensitivity test, to categorize the participants as less or more sensitive to glare. The light intensity at which a participant's discomfort glare rating changes from 'No' discomfort to 'Yes' discomfort on the binary scale was taken as BCD (borderline between comfort and discomfort) value for that participant. If the borderline value was lower than or equal to the middle level intensity (scene 10%), the participant was categorized as less sensitive to glare and if it was higher than mid-intensity than the participant was categorized as more sensitive to glare.

The MPOD distribution for OD (right eye) and OS (left eye) is reported as density plots. For those participants where the pigment density was different in OD and OS, we took the minimum of the two values for the analysis. We applied Wilcoxon rank-sum test (Wilcoxon, 1945) for comparing two independent non-parametric samples to determine if there is a significant difference at $\alpha=0.05$ in the MPOD levels between the less and more sensitive groups.

4.4 Results

The analysis outcomes for the 53 participants showing consistency in their ratings are presented in the following subsections.

4.4.1 Subjective responses to glare

Subjective responses to glare, as reported by the participants, were analysed for each of the experimental conditions listed in Table 4-1. The resulting distribution of glare votes for each glare level is shown in Figure 4-4 for the binary glare scale and in Figure 4-5 for the 6-pt glare scale.

In general, the subjective glare responses follow the glare source luminance. Increase in luminance increases the discomfort glare perceived by the participants, thereby validating the experimental protocol followed. Similar trends can be observed in the responses on both scales in Figure 4-4 and Figure 4-5. However, the threshold between discomfort and comfort tends to get lower with the 6-pt scale compared to the binary scale: even if participants experienced a slight discomfort, they would tend to report no discomfort on the binary scale. This can be due to the finer classification of the scale and the semantic differences in the scale labels. Of all the participants who voted "Slight discomfort" on the 6-pt glare scale, 53% had voted "Yes" on the binary scale. Since binary scale provides a clearer semantic distinction between comfort and discomfort, we decided to derive the glare thresholds for each participant based on the glare voting done on the binary glare scale. The Spearman's rank correlation coefficient between the glare source luminance and the subjective responses reported on 6-pt scale was 0.71, which is indicative of a strong effect size following Cohen's standard (Cohen, 1988).

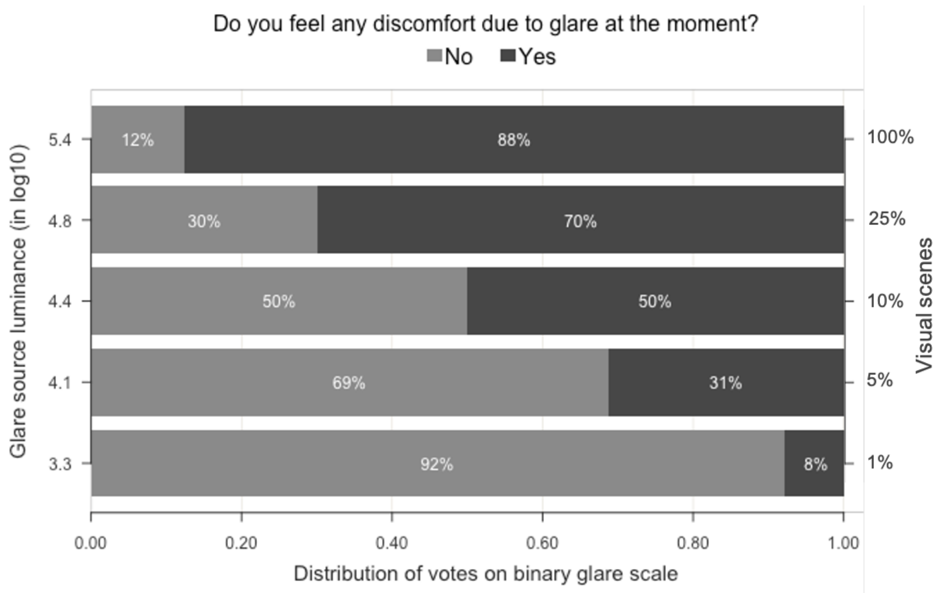


Figure 4-4 Distribution of participant's response to glare levels on binary glare scale

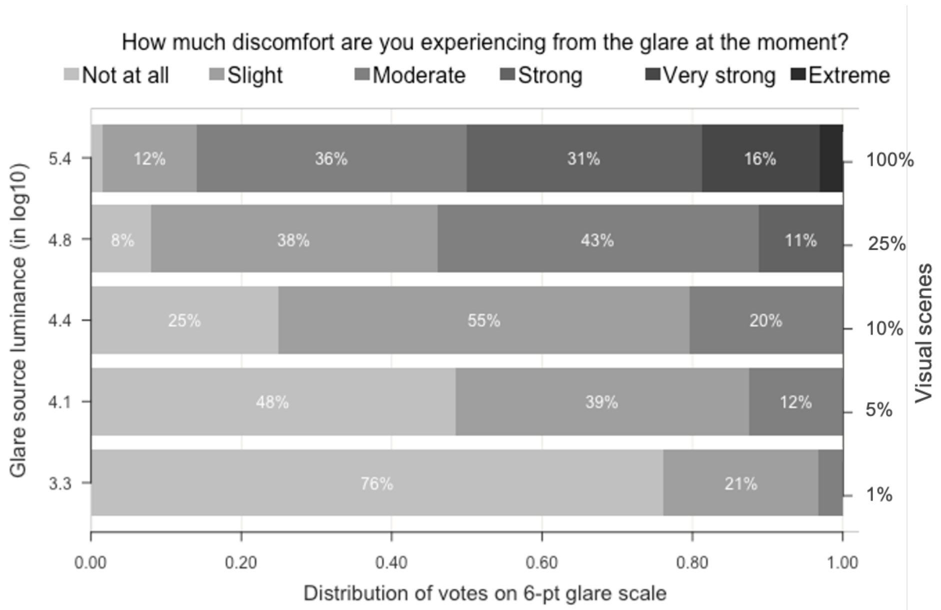


Figure 4-5 Distribution of participant's response to glare levels on 6-pt scale glare scale

4.4.2 Glare thresholds

Based on the participants' responses to glare on the binary scale, we derived glare thresholds for each participant, i.e., their borderline values between comfort and discomfort. As shown in Figure 4-6, the resulting discomfort glare thresholds are well distributed across the range of light intensity shown to the participants, which indicates quite some inter-individual variability in comfort perception. The glare thresholds obtained from the sensitivity test were in agreement with those obtained from the post-trial session (Pearson's correlation coefficient ρ=0.61). Based on the glare level categorization rules described in section 4.3.4, we found that 47% of the participants to be less sensitive and 53% more sensitive to glare in our sample.

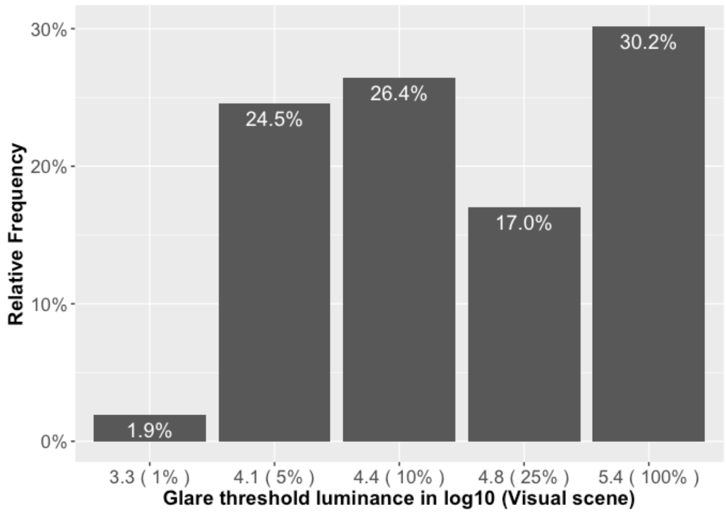
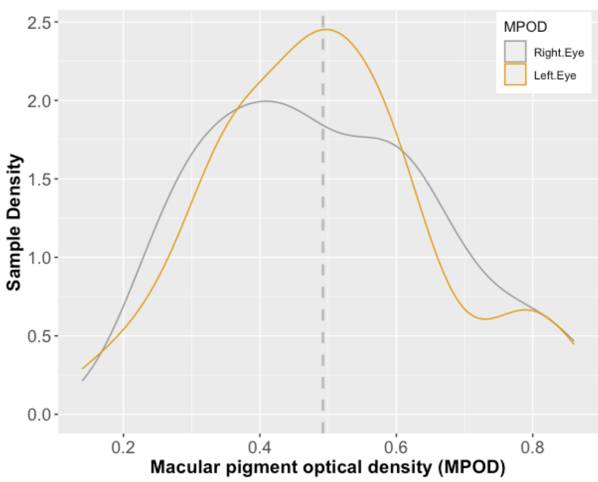


Figure 4-6 Distribution of participant's glare threshold luminance values

4.4.3 MPOD and glare sensitivity

The MPOD levels among the sample were found to range from 0.14 to 0.86, with mean MPOD measurements for OD and OS of 0.49 and 0.50. The correlation coefficient of mean MPOD measurements of OD and OS was 0.87 (Pearson correlation coefficient, P<0.0001), indicating excellent inter-eye predictability of the measurement device. Figure 4-7 presents the distribution of the MPOD for the left and the right eye which follows a normal distribution (Shapiro–Wilk test, P=0.32 and 0.06). We selected the minimum of OS and OD as an indicator of MPOD for a participant for the analysis purpose.

We then compared the mean differences in MP levels between the two groups of the participants categorized as less and more sensitive to glare by applying a Wilcoxon rank-sum test on the two groups (Figure 4-8). We found statistically significant differences in MPOD between the two groups at α=0.05 (Wilcoxon test p=0.028 with small effect size, ρ=0.30), which shows that further investigation on MP would seem promising to provide new insights on the factors influencing glare perception. Figure *4-8* shows the boxplots of the two groups together with the mean values of MPOD: MP levels were actually found to be slightly higher in the more sensitive group compared to less sensitive groups, which contradicted our expectation and warrants further investigation.



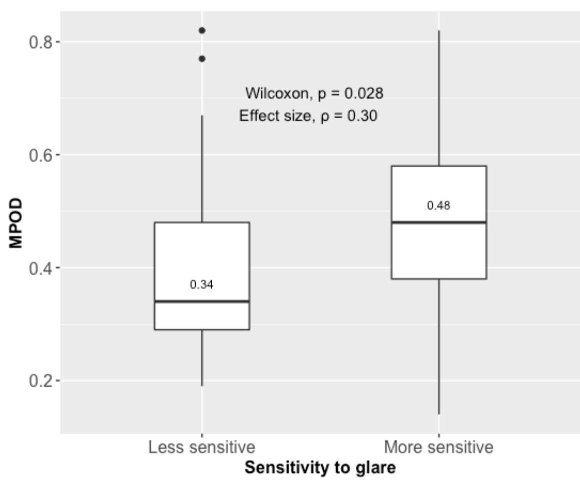


Figure 4-7 (left) Distribution macular pigment optical density in the sample population

Figure 4-8 (right) Comparison of MPOD values in the two groups less sensitive and more sensitive to glare

4.5 Conclusions and discussion

This study contributes to the present knowledge on discomfort glare sensitivity and its relationship with macular pigment. In addition, this study provides a methodological approach to quantify individual glare sensitivity thresholds. The method was found to be consistent in evaluating within-subject responses.

In this study, we evaluated a person's sensitivity to glare and compared it with their measured MPOD levels. MPOD levels were found to be *borderline* statistically different between the two groups of participants (less vs. more sensitive to glare) but with a *small* effect size. We found slightly lower MPOD in the group having higher glare thresholds: this is surprising since it contradicts the previous studies. One explanation could be that most of the previous studies were conducted under disability glare levels and the glare source was visible within foveal range. However, in this study we have discomfort glare scenarios with glare source visible outside the fovea. Since macula covers about 6.7° in the horizontal and 3.0° in the vertical directions of the central retina, its influence is likely to decline towards the perifoveal light sources that occurs in our experimental scenarios.

The limitations of the study also have an impact on the accuracy and the generalizability of the results. In our experiment, the exposure to glare conditions was very short-term and subjective assessment of glare can vary with longer exposure time. Previous studies give us indications about the variation in average macular pigment density as per the ethnicities of the sample, for example, Davey and authors (Davey et al., 2020) found higher pigment density in south Asian Indians and Hispanics compared to Caucasians and African Americans. However, in our study, we didn't control for ethnicity of the participants and due to small sample size, we assumed the same averages across the recruited participants of different ethnicities. Additional data is needed to validate the finding and more in-depth analyses are required to confirm the results obtained in this preliminary analysis.

In the next steps of the study, in collaboration with Hospital Ophthalmic Jules-Gonin, we will be employing physical method of Fundus autofluorescence imaging to examine the macula. We will also measure the photostress recovery time in our sample, which is closely linked to macular pigment and glare sensitivity. We will extend the protocol to daylit scenarios and increase the exposure time to the experimental conditions to better replicate the typical office conditions.

Acknowledgement

This study was conducted within the framework of a broader collaboration with the Hospital Ophthalmic Jules-Gonin and the authors would like to thank Prof. Aki Kawasaki and Prof. Chiara Eandi for their insights on these initial results. The work is funded by Swiss National Foundation project (SNF) grant for the project "Visual comfort without borders: interactions on discomfort glare" number 200020_182151.

Key outcomes of this study are:

- A methodological approach to quantify individual glare sensitivity thresholds where within subject glare responses from the participants were found to be consistent.
- MPOD distribution do vary among the selected sample population, which is consistent with the literature, even though the sample is derived from a homogenous young and healthy group of participants.
- Participants' measured MPOD levels were found to have only borderline significant differences between the less sensitive and more sensitive groups of the participants.

This study connects to the upcoming chapter in following ways:

- The methodology to categorize participants into less and more sensitive groups was further applied in the subsequent chapter that evaluates influence of MPOD on discomfort glare from daylight.
- Participants' glare sensitivity derived from the electric light was further compared with their sensitivity from daylight glare to check whether the two are consistent for a participant.

Chapter 5

Influence of macular pigment on the sensitivity to discomfort glare from daylight

Objectives

The objectives of the study presented in this chapter are:

1.The primary objective is to determine the influence of macular pigment on the discomfort glare sensitivity from the sunlight filtered by color-neutral and blue glazing.

2.The secondary objectives are to determine the influence of ocular parameters that are linked to macular health, mainly the photostress recovery time and retinal thickness, on the discomfort glare sensitivity from the sunlight filtered by color-neutral and blue glazing.

Influence of macular pigment on the sensitivity to discomfort glare from daylight

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Abstract

Understanding the factors that influence the human perception of glare is necessary to properly address glare risks in buildings and achieve comfortable visual environments, especially in the workplace. Yet large inter-individual variabilities in glare perception remain unexplained and thus uncovered by the current empirical glare models. We hypothesize that this variability has an origin in the human retina, in particular in the density of macular pigments present in its central area, which varies between individuals. Macular pigments are known to absorb blue light and attenuate chromatic aberration, thus reducing light scatter. This study presents the outcomes of the first experiment ever conducted in a daylit office environment, in which glare sensitivity and macular pigment density were measured and compared for 55 young healthy individuals, along with other ocular parameters. The participants were exposed to different glare conditions induced by the sun filtered through color-neutral vs. blue-colored glazing. In neutral daylight conditions with sun disc in near peripheral FOV, neither macular pigment nor any other investigated ocular factors have an impact on discomfort glare perception whereas glare perception in conditions with blue-colored sun disc in the near periphery was found to be correlated with macular pigment optical density.

Keywords: Discomfort Glare, Daylight, Macular pigment, spectral sensitivity

5.1 Introduction

Designing buildings that facilitate optimum utilization of daylight is desirable for its many benefits including occupant well-being, productivity, energy conservation, and building sustainability. Nevertheless, it remains a source of light challenging to manage, given its dynamics and its associated over-heating and glare risks (P. Boyce et al., 2003; Leather et al., 1998a). Excessive brightness from daylight in workplaces can indeed lead to discomfort glare which, if prolonged or recurrent, might reduce occupant wellbeing, mood, and performance.

Discomfort glare has actually been studied for several decades and the prediction models resulting from the conducted user assessment studies are nowadays able to provide a reasonable estimate of discomfort for a group of observers (Wienold et al., 2019b). However, glare models often perform poorly when it comes to individual comfort due to the large inter-individual variability in glare perception (Mainster & Turner, 2012). Since the physiological origin associated with discomfort glare mechanisms is not well understood, the factors for the variability in the users' perception cannot be included in current glare models. Existing glare models only account for various physical/geometrical factors related to the source(s) of light present in one's field of view. However, before potentially generating discomfort, light must first reach the neural signals and this process occurs in the eye itself. Therefore, it would be worth investigating certain anatomic-physiologic features of the eye, focusing on those which, based on the available literature, are more likely to influence glare perception and thus generate variance between individuals, with the ultimate goal to improve glare prediction models.

One such ocular factor, most studied in the ophthalmology literature, is the density of yellowish macular pigments present in the fovea. Individuals with higher macular pigment density were reported to have better visual performance and higher tolerance to glare from electric lighting close to the fovea (Hammond et al., 2013; Pierson et al., 2018b; Stringham et al., 2004b, 2011b; Wenzel et al., 2006a; Wilson et al., 2021). Macular pigments (MP), which are greatest in the foveal region (6.7° horizontal, 3.0° vertical) and decrease exponentially with increasing eccentricity from the center of the fovea (Bernstein et al., 2010; Wyszecki & Stiles, 1982), have absorption spectra between 400nm to 550nm, peaking at around 460nm i.e. in the blue range of the light spectrum (CIE 170-2: 2015, 2015). MP acts as a filter for short-wavelength blue light and reduces the scattered light reaching the photoreceptors. Its impact on blue light attenuation is measured by the so-called Macular Pigment Optical Density (MPOD), which is linearly related to the amount of carotenoids (lutein and zeaxanthin) present in the macula (Bernstein et al., 2010). All the studies on glare and macular pigment interactions measured MPOD using heterochromatic flicker photometry (HFP) (van der Veen et al., 2009b) method on a scale of 0 to 1, where higher values indicate better attenuation of blue light hitting the macula. There exists a wide variability in the amount of macular pigments across the population, therefore, causing a large variation in the amount of short-wavelength light processed by the retina (Stringham, Bovier, Wong, & Hammond, 2010). Based on this, it could be hypothesized that the existing variability in sensitivity to glare could be partly caused by the variability in macular pigments.

Stringham et.al (Stringham et al., 2011a) indicated that higher MP levels in the participants significantly improved their photostress recovery and visual performance in glare conditions. Another study from the same authors (Stringham et al., 2004a) showed that the participants with the broader spatial distribution of macular pigments (i.e. covering a greater range beyond fovea) had higher photophobia thresholds which were further confirmed by Wenzel et. al (Wenzel et al., 2006a). Hammond et al. showed a significant contribution of MP in protection against disability and discomfort glare (Hammond et al., 2013). A recent study by Wilson et al. showed that individuals with significantly higher MPOD levels experienced less eye pain or fatigue in their day-to-day activities assessed via questionnaires (Wilson et al., 2021). In addition to discomfort glare, few studies have also assessed the impact of MP on disability glare and photostress recovery time (time taken to reach normal acuity after bleaching of photoreceptors by bright light) and found similar results(Hammond et al., 2013; Stringham et al., 2011a). However, Loughman et al. concluded that the visual performance under glare conditions was unrelated to macular pigments. Authors discussed that the absence of a strong blue light component (absorbed by MP) in their white LED light source, might be reason of their findings being different than the other studies. Although, a later study by Stringham et al. also used white LEDs with lesser blue content but still found that MP influenced glare sensation (Stringham et al., 2011a). Given the significant findings demonstrated by many studies, macular pigments remain a promising factor that can potentially influence glare perception.

We should note that all the research on the relationships between MP and discomfort glare were conducted until now under ophthalmological laboratory settings, with a light source projected on the retina, with a visual angle between 1° to 6° in order to measure the glare sensitivity in foveal and parafoveal regions where MP is concentrated (Stringham et al., 2004a; Stringham & Hammond, 2008; Stringham & Snodderly, 2013; Wenzel et al., 2006a). These conditions differ significantly from realistic settings and thus limit the applicability of the findings to the normal indoor environment. It is indeed not known whether the influence of macular pigment would persist in normal working conditions i.e. where glare sources do not usually lie in the fovea, occupants have unrestricted gaze behavior, and where the main source of glare has a broader spectrum, such as in the case of daylight from windows (or – though to a lesser extent – of electric luminaires). Such investigations can provide complementary answers to the studies discussed above, with more direct applicability to the larger context of indoor workplace environments.

Towards this end, this study aims to determine the influence of macular pigment optical density on the discomfort glare perception under daylight conditions in an office-like setting where the sun visible through the window act as a main glare source.

We present the findings from two user experiments with 55 healthy participants each (age: 18-35 yrs.): one with color-neutral glazing (experiment I) and another with blue-colored glazing (experiment II). We measured the participants' MPOD levels and compared them with their glare perception assessed psychophysically by exposing them to four varying levels of sun intensity visible behind the glazing in each experiment. In experiment I, test conditions had color-neutral glazing that differed in glazing transmittance whereas in experiment II, conditions differed in glazing color (blue, green, red, neutral, a set that was designed as part of another study). The present analysis will be restricted to glare evaluations based on the full set of color-neutral scenarios from Experiment I and on the blue glazing scenarios from Experiment II only. Blue glazing was chosen as light absorption by macular pigments is the highest in the short wavelength region whereas color-neutral glazing was chosen to represent regular office environments. In Experiment I, all participants took part in an additional two-hour long session at the ophthalmic hospital where relevant functional and structural eye exams were conducted for assessing their macula and ensuring a normal fundus without any retinal pathologies. Alongside measuring MP levels in experiment I, we also assessed macular photostress recovery time following bright light exposure and measured participants' iris thickness in relation to their glare perception.

The primary objective of the study is to determine the influence of macular pigment on glare sensitivity under daylight and the secondary objectives are to determine the influence of functional and structural parameters that links to macular health, mainly the photostress recovery time and retinal thickness. To the best of our knowledge, this is the first-ever study that investigates the influence of macular pigment density on glare sensitivity under natural lighting conditions.

5.2 Method

5.2.1 Study design

The two experiments with 55 participants each were conducted in Lausanne, Switzerland (46°31'00.4" N, 6°33'47.1" E) during the winter months (Nov'20 – Mar'21 and Nov'21 - March'22) to benefit from low sun angle. Both experiments followed the same psychophysical approach, where the relationship between the participants' measured ocular parameters and their subjectively assessed glare sensitivity is investigated. In the first study conducted under color-neutral daylit scenarios (experiment I), each participant took part in two test sessions of two hours each: i) first session on the EPFL (Ecole Polytechnique Fédérale de Lausanne) campus where the participants' subjective perception of discomfort glare from daylight and electric light was assessed; ii) second session at the HOJG (Hôpital

Ophtalmique Jules Gonin) where the participants' had some of their structural and functional ocular parameters measured. In the second study under colored daylit scenarios (experiment II), participants took part in a single session at the EPFL campus, which followed the same protocol as the first session of experiment I. All tests at EPFL were conducted on clear sky sunny days with stable weather so as to use the sun as a glare source visible behind the glazed façade. The tests at HOJG for Experiment I were scheduled according to the availability of the staff and the equipment.

5.2.2 Participants

We recruited a total of 55 participants in each of the two experiments based on a pre-selection questionnaire and following the same eligibility criteria. These were to: be in healthy conditions, not be diabetic, have normal color vision, have no other visual impairment, have a BMI within the normal range, and have no extreme chronotypes (chronotype assessed using Morning-Evening Questionnaires (Horne & Östberg, 1976)), have an English proficiency level C1 or higher, not use drugs and not abuse of alcohol, and be aged between 18 and 35 years. To avoid response bias, an additional exclusion criterion was to be from a discipline related to the investigated field (i.e., architecture and civil engineering) or to have a link to the researchers' topic or the laboratory. Table 5-1 summarizes the participants' resulting demographics (number, age, gender, iris color, and vision correction). The project protocol was approved by the cantonal ethics commission *Commission Cantonale d'éthique de la recherche sur l'être humain* (Lausanne, Switzerland, ref. No. CER-VD 2020-00667). Participants gave written informed consent before the experiments and were compensated as per local regulations.

Table 5-1 Demographics of the participants

Experiment	**No. of participants**	**Age (in years)**	**Sex**	**Vision correction**	**Iris color (self-reported)**
Experiment I	55	Min=18 Max=34 Mean=23	72% Male 28% Female	64% No correction 36% Glasses or lenses	18% Black 22% Blue/Green/Grey 60% Brown/hazel
Experiment II	55	Min=18 Max=30 Mean=22.6	71.5% Male 28.5% Female	53.6% No correction 46.4% Glasses or lenses	19.6% Black 26.8% Blue/Green/Grey 53.6% Brown/hazel

5.2.3 First session at EPFL (Experiments I & II)

5.2.3.1 Test room setup

The participants' sensitivity to glare from daylight and electric light was evaluated at the EPFL campus in an office-like test room (3.05m x 6.55m), shown in Figure 5-1. The test room is fully equipped to control and measure indoor visual and thermal parameters and was used in previous user studies related to comfort (Chinazzo et al., 2018; Jain et al., 2023; Jain, Karmann, et al., 2022). The room temperature was continuously measured and monitored to keep it within comfortable ranges (21 ± 2°C) using an indoor climate meter equipped with temperature, humidity, airflow, and CO_2 sensors. We measured the visual parameters of the room including horizontal illuminance at the desk and vertical illuminance at eye level using lux sensors and measured the daylight spectra at eye level using a spectrometer. We used a calibrated luminance camera LMK 98-4 with a fisheye lens (type Dörr Digital Professional DHG, equidistant projection) to capture high dynamic range (HDR) images of all the experimental conditions from each of the participants' viewpoints before and after their exposure to the condition. To capture the sun without any pixel overflow, we used neutral density filters ND4 (factor 9366) in experiment I and a combination of two ND1.8 filters (with a combined factor ND3.5 3134) in experiment II. A handheld illuminance sensor was mounted below the lens of the camera to compare collected data to the illuminance values derived from the HDR images. Images were captured using the Labsoft software provided with the LMK camera.

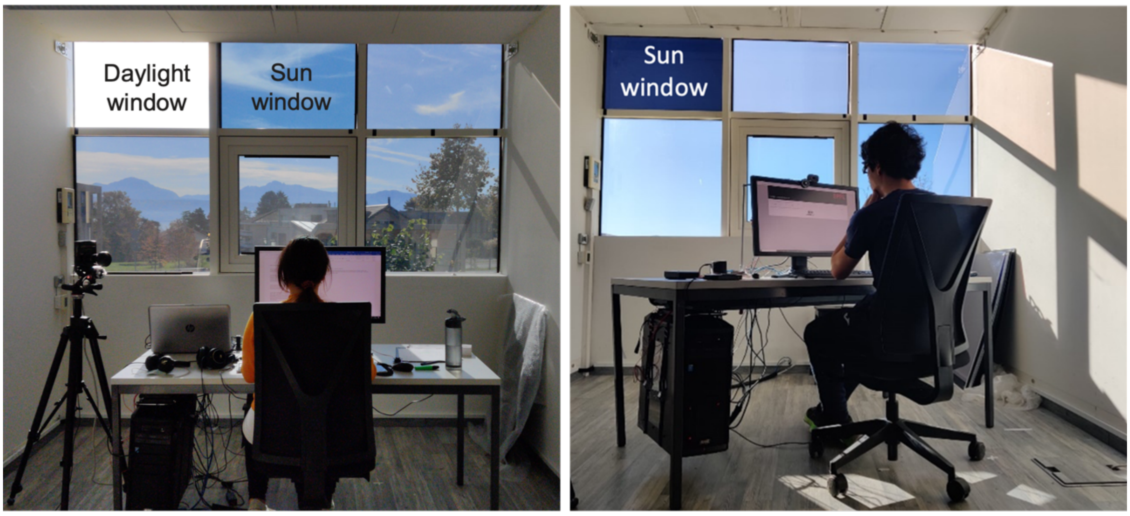

Figure 5-1 Participant performing the test, left: in experiment I under color-neutral glazing; right: in experiment II under blue-colored glazing

5.2.3.2 Test Protocol

The overall experimental protocol pertaining to the EPFL session is summarized in figure 5-2 and was the same in both experiments I and II. Experiments were conducted sometime between 9h and 15h with one participant at a time present for two hours. The first part of the experiment was conducted under constant electric lighting conditions with closed window blinds (i.e., no access to daylight) and after that, participants were exposed to the four experimental conditions with daylight as the only source of light (all electric lights switched off).

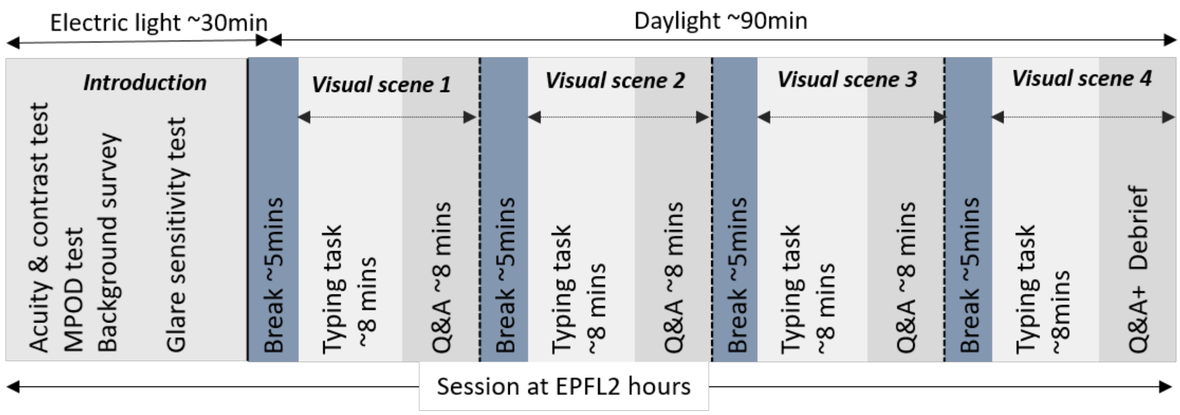

Figure 5-2 Test procedure at EPFL

Upon arrival, the participants were briefed about the test protocol by the researcher following a single-blind procedure and were asked to sign their written consent to participate. They did the visual acuity and contrast sensitivity tests using the validated software FrACT 3.10.5 (Bach, 1996b) on a computer screen at a distance of 170 cm from the screen to allow the measure of the maximal acuity. The brightness of the computer screen was calibrated once using a luminance meter. Afterward, the participants filled out a background questionnaire answering about their demographics, indoor environmental preferences, and their current physical and emotional states. The researcher measured the participant's macular pigment optical density (MPOD) in the foveal region of the retina using a macular pigment screener device QuantifEye MPS II (*MPS II: Technical Profile*, n.d.) that employs heterochromatic flicker photometry to provide an estimate of the blue light absorption by MP. MPOD values are measured on a scale of 0 to 1, where a lower value indicates a higher level of blue light hitting the macula. In this test, the participants viewed a centrally fixated target and made flicker matches at two light wavelengths: one at 465nm (blue light), which is absorbed by the MP, and the other at 530nm (green light), not absorbed by MP. Afterwards, a glare sensitivity test was conducted to determine the participants' sensitivity to glare from electric light in a psychophysical procedure using a dimmable electric light source (only in experiment I). The details of the test and resulting analyses can be found in the CIE 2021 conference proceedings (Jain, Wienold, et al., 2021). That sensitivity test was followed by a break as shown in Figure 5-2: during the break, an eye mask was placed on the participant's eyes for about five minutes to ensure dark adaptation, while the researcher set the test room up for the next tests, all conducted under daylight.

After the break, the participants were seated facing the glazed façade on the south as shown in figure 5-1 left, with the sun apparent in their central field of view. The participants were exposed to four different daylight conditions, experienced in a randomized order and each preceding a dark-adapted break of approximately five minutes, as shown in figure 5-2. During the exposure to each condition, the participants performed a typing task to adapt to daylight and simulate an office environment. Afterwards, they assessed the discomfort caused by glare based on different glare rating scales through a questionnaire to be filled out on screen. During each between-condition break, participants wore an eye mask while the researcher changed the glazing panel to create the next experimental condition and recorded the current luminous conditions. A luminance camera was used to this end by the researcher to capture HDR images of each experimental condition at the participant's eye level before and after exposure. These images were later processed to calculate the discomfort glare metrics corresponding to each test condition. At the end of the full experiment, participants answered a debriefing questionnaire to provide their overall impression. This part of the protocol, conducted under daylight only, lasted about 90 minutes.

5.2.3.3 Test conditions

The four daylight glare conditions experienced by the participants were achieved by altering the glazing transmittance of the windowpane from where the sun was visible to them (labeled as 'sun window' in Figure 5-1). The tests with daylight were conducted only under stable weather on the clear sky (sunny) days, to ensure consistent and similar daylight availability between all the collected datapoints. The specifics of the test conditions, especially regarding daylight spectrum and intensity, are described below for experiments I and II.

Experiment I

In experiment I (Figure 5-1, left), we applied color-neutral films of specific visible light transmittance onto clear acrylic sheets ($\tau_{v,}$ = 95%) that were manually fixed against the windowpane of the south façade to vary the transmittance of the sun window and thus create the different test conditions. The four conditions under color-neutral tints are referred to as T1, T2, T3, and T4, with measured normal-hemispherical sun window transmittance ($\tau_{v,n\text{-}h}$) of 0.36%, 1.25%, 3.4%, and 4.8%, respectively. One windowpane, labeled 'Daylight window' in figure 5-1 (left), was kept at its maximum transmittance of 79% under all four conditions to achieve sufficient daylight levels in the room i.e. at least 300 lux at the desk, which is deemed suitable for office work (CEN, 2019). The other four windowpanes were kept at a constant transmittance of 4.8%, chosen to avoid glare risks while at the same time maintaining a clear view to the outside. As a result of this setup, the four created conditions, shown as fisheye HDR images and as falsecolor luminance maps in Figure 5-3, differed in terms of the luminance of the sun seen through the sun window and the total vertical illuminance reaching the participants' eyes, thus creating different levels of glare conditions for the participants. To maintain the same viewing direction between the sun and any participant's view direction in all four conditions, the participant's desk was rotated as per the sun's apparent position during the experiment. Figure 5-4 provides the spectral transmittance of the four types of "sun windows" (combining the film, acrylic sheet, and fixed glazing) used to create the test conditions in experiment I. We measured the spectral transmittance of each glazing unit (combination of colored filter and fixed window) and their angular behavior in a specialized glazing and Nano-tech laboratory by following the setup described by Steiner et al. with a measurement uncertainty of 0.001 (R. Steiner et al., 2005).

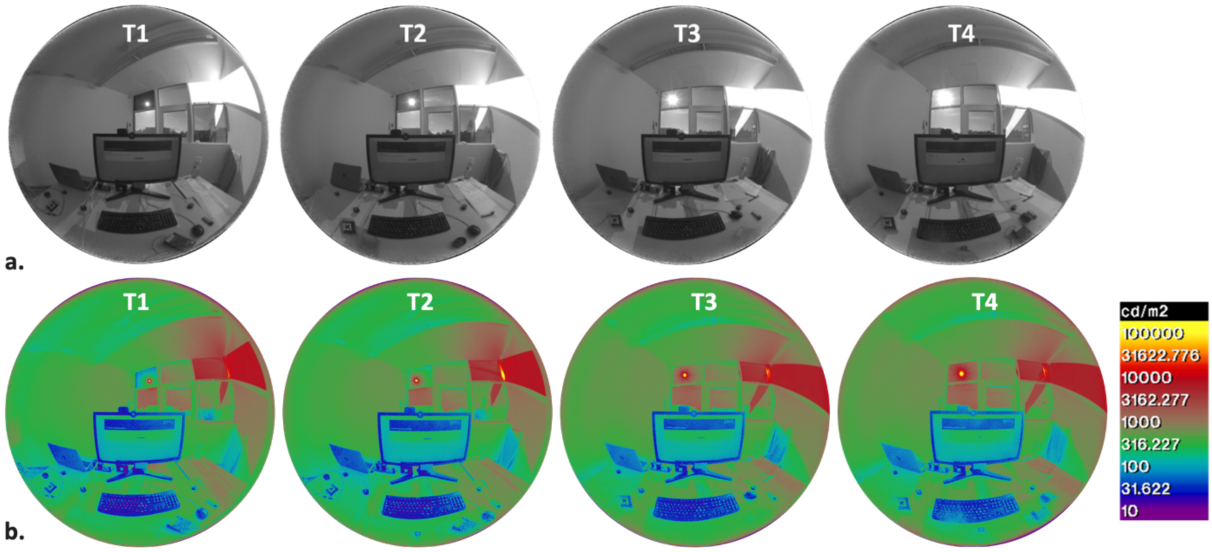

Figure 5-3 a. Fisheye images of the test condition b. Falsecolor version of the images showing the variation in the sun luminance in four experimental conditions

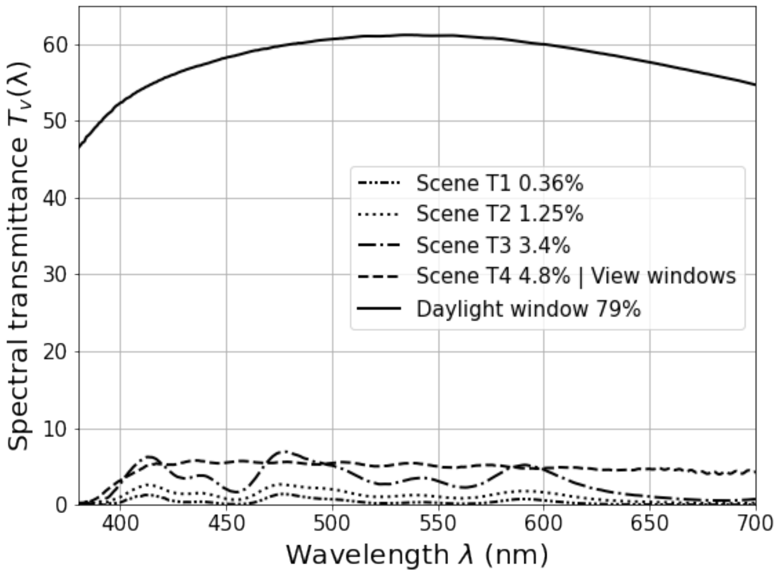

Figure 5-4 Spectral transmittances of the glazing used in experiment I

Experiment II

In experiment II, all participants were exposed to four daylight conditions differing in the color of the glare source, using blue, green, red, and color-neutral glazing, and that were either of extremely low transmittance or of low transmittance. The overall experiment was designed for a different goal that is unrelated to this study, namely to determine the effect of color on glare perception, using two different brightness ranges. In the present study, we will only consider the data collected in the blue glazing conditions, for both the less transmissive sun window glazing (condition B1, sun window $\tau_{v,n\text{-}h}$ =0.39%, experienced by 27 participants) and the more transmissive one (condition B2, sun window $\tau_{v,n\text{-}h}$ =2.25%, experienced by 28 participants), whose spectral properties are provided in Figure 5-5 together with the color-neutral glazing's. Both the B1 and B2 conditions are illustrated in Figure 5-6: similarly, to experiment I, only the sun window's transmission properties were varied between conditions while the remaining windows, all color-neutral, were kept at a constant transmittance of 8% to avoid glare and maintain a clear view.

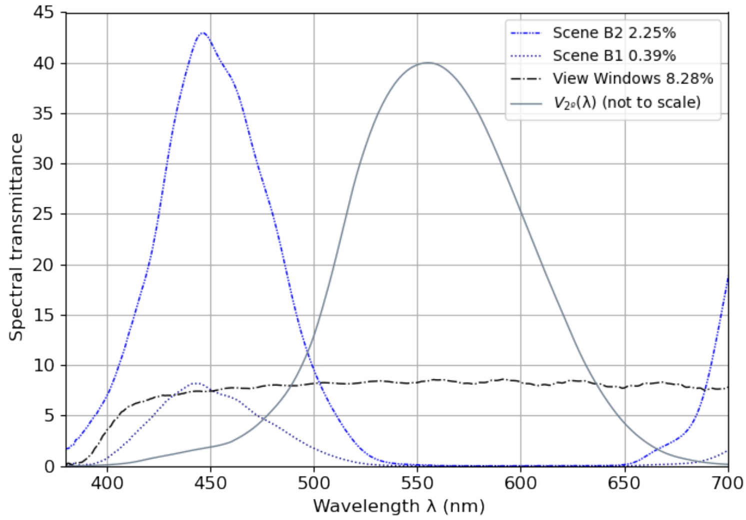

Figure 5-5 Spectral transmittance of the glazing used in experiment II

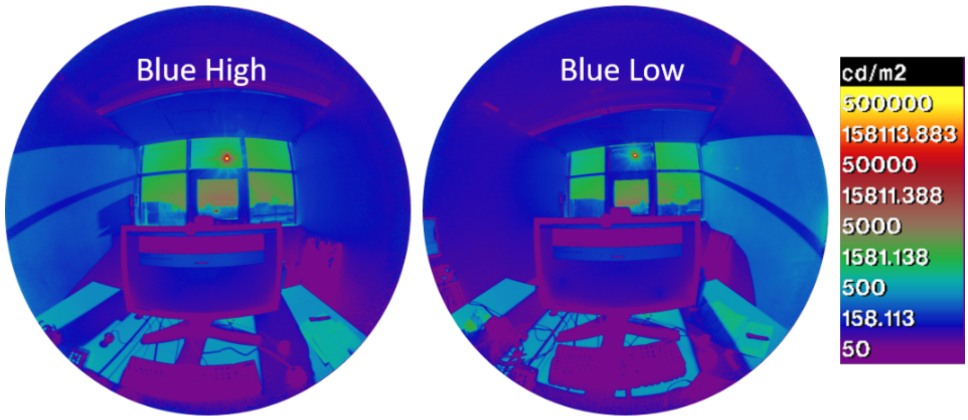

Figure 5-6 a. Fisheye images of the test conditions experienced by the participants in experiment II with the blue-colored glazing; b. falsecolor version of the same images, showing the luminance distribution

5.2.3.4 Subjective assessment

During the experiments, participants answered three web-based surveys: 1) a background questionnaire to be filled out at the beginning of the experiment about the participants' demographics, mood, and indoor environment preferences, 2) a comfort questionnaire provided after exposure to each daylight condition about the visual and thermal comfort, discomfort glare perception, color perception and view out perception, and 3) a debriefing questionnaire provided at the end of the experiment to get an overall feedback on the experiment and the test conditions.

In this section, we go into detail only for the questions from the second type of questionnaire that pertain to discomfort glare or eye fatigue, as these constitute the main focus of the study. Table 5-2 lists the questions which were analyzed in relation to the participants' ocular characteristics (cf. Results section): these questions were designed to minimize potential response biases by careful framing of the questions and by using response labels that followed the suggestions and examples found in visual comfort literature (Chinazzo et al., 2018; W. Osterhaus & Bailey, 1992; Pierson, 2019b). The order in which the questions were asked was randomized in the survey to avoid any order bias. These questions were answered based on either a binary scale, a Likert (ordinal) scale or linear response labels, or in one case as a free text as shown in Table 5-2.

Table 5-2 Survey questions and their response labels pertaining to discomfort glare

Question	Response items
1. Is there anything about the physical environment that disturbs you in this moment?	Open-ended text field
2. Are you experiencing any discomfort due to glare at the moment?	Yes – No
3. At the moment, how would you describe glare in your field of view?	Imperceptible - Noticeable - Disturbing - Intolerable
4. How much discomfort due to glare are you experiencing at the moment?	Not at all – Slightly – Moderately – Very much
5. On a scale of 0-10, how much discomfort due to glare are you experiencing at the moment?	Not at all 0-1-2-3-4-5-6-7-8-9-10 Very much
6. Are you experiencing any eye fatigue or pain on your eyes?	None – Slight – Moderate – Severe

The first survey question was the open-ended question (question 1 in Table 5-2) that allowed participants to report any disturbance due to the physical environment of the room but without drawing their attention to any specific comfort parameter (such as glare). We evaluated the answers to this question to check if the participants would mention glare spontaneously in their answers since this was the only independent variable varying in the tested conditions. Questions 2, 3, 4, and 5 in Table 5-2 were asked to inform on the participants' glare perception under daylight conditions. We asked the same question on different response labels to ensure consistency between a participant's answers and check the internal reliability of the questions. Question 6 is adapted from the visual functioning questionnaires (Mangione et al., 1998) to inform on eye fatigue or ocular pain caused by working under each lighting condition and determining its relation with participants' macular pigment density.

5.2.4 Second session at HOJG (Experiment I)

In Experiment I, an additional session of ocular examinations was conducted at the ophthalmic hospital to perform an in-depth analysis of various structural and functional aspects of the retina and their relationship with glare sensitivity. After completing the subjective glare assessment test at EPFL, participants visited the HOJG within a couple of days to participate in standard eye exams under the supervision of an ophthalmologist at HOJG. This session took about 2-2.5 hours in the late afternoon from 14h30 to 17h. All participants were first screened by their pathology history, visual acuity, and fundus examination to ensure the absence of ocular pathology. Thereafter they underwent additional structural and functional tests of the macula which include: contrast sensitivity, automated perimetry, pupillometry, photostress recovery time, optical coherence tomography, and auto fluorescent fundus imaging as detailed below:

1) Fundus photography autofluorescence (FAF): This test was conducted with Zeiss Clarus widefield digital camera. This photography uses blue light filters in order to detect lipofuscin photopigment abnormalities across the retina. FAF imaging aimed to aid in the documentation and diagnosis of any ocular pathology among the participants.
2) Optical Coherence Tomography (OCT) of iris: This test was conducted using Optovue OCT Model Avanti, Fremont, CA, USA with a laser emission of 840 nm. The iris thickness was estimated from the mean of two cross-sectional images of the anterior segment at 0°-180°, and 90°-270° degree meridians under mesopic conditions for medium pupillary constriction (the pupil was illuminated so as to obtain a diameter of 5mm in each participant).
3) Pupillometry: Neurolight by IDMed was employed as a portable integrated device to record pupil response to pre-determined light stimuli. This portable integrated device combines a retinal stimulator and pupil recording in a compact instrument using 4 different LEDs and infrared photo

video recording at 60 Hz. The pupil response to pre-determined light stimuli was recorded and analyzed to assess outer and inner retinal photoreceptor activity. Using light stimuli in different wavelengths, the different photoreceptors (rods, cones, and melanopsin) are targeted.
4) Contrast sensitivity (2.5%): This test measures visual acuity under low contrast conditions. Participants were scored based on the reading of a Pelli-Robson precision vision chart to ensure normal vision.
5) Photostress test: This test measures the time taken by the participant to return to their normal visual acuity following 10 seconds of bright light exposure.

5.2.5 Data cleaning and processing

We established data filtering criteria to ensure the reliability and homogeneity of the collected photometric data and to ensure the absence of any ocular pathologies among the participants. Following are the filtering criteria and procedure carried out to clean the data:
1) We discarded the test cases where the deviation in measured on-site global horizontal irradiance (GHI) was more than 25% ((GHI_{max} - GHI_{min}) / GHI_{mean}) to ensure stable daylight conditions during the entire exposure time and no intermittent clouds occluding the sun.
2) We discarded test cases where the sun was hidden from the participant's FOV by the window frame or by other elements by manual inspection of the HDR images taken from the participant's eye position to ensure that the sun stay in the user's FOV as a glare source.
3) Test cases where the HDR images were found overexposed due to a camera error that couldn't be resolved to obtain accurate luminance maps were discarded.
4) Data from two participants were discarded because the manual qualitative assessment of the images from the participants' OCT exam revealed an abnormal iris profile due to a scar on the iris in one case and relative loss of foveal depression in another case.
5) FAF images were graded by two ophthalmologists independently for hyper- or hypo- fundus autofluorescent abnormalities. In case of disagreement, a third ophthalmologist resolved them. Based on the qualitative assessment of FAF images, data from one further participant was discarded where focal abnormalities were found at the temporal periphery in both eyes.

We post-processed the captured HDR images of the experimental scenes to derive glare metrics and photometric quantities from the luminance maps of the images. Scene images were first converted to ". hdr" format from ".pf" (picture float) format. They were inspected for pixel overflow, which was found in 16 cases where the pixels in the sun disc were saturated, and the image-derived vertical illuminance values were substantially lower (>25%) than the measured ones. To correct these images, we replaced the overflow pixels to match the measured vertical illuminances. These images were then processed in the Evalglare tool (Wienold, 2004), which is part of the Radiance lighting simulation engine (G. J. Ward, 1994), to derive the glare metrics which were used to compare the experimental conditions.

5.2.6 Statistical Methods

Descriptive analyses were conducted to characterize the collected photometric and physiological data with the help of scattered box plots, density plots, and stacked bar plots. To determine the influence of MPOD and other measured ocular parameters on glare sensitivity under daylight conditions, we applied several non-parametric tests. We used a pairwise Wilcoxon signed rank test (Wilcoxon, 1945) to compare the mean MPOD measures between the participants reporting glare and participants not reporting glare on binary glare questions under each daylight experimental condition. We conducted correlation analyses to determine the association between the glare responses and the ocular measurements. To correlate responses on binary labels with the MPOD, PSRT, and iris thickness, we applied the Point-biserial correlation coefficient, which is applicable when one of the two variables is dichotomous (Gene V. Glass & Kenneth D. Hopkins, 1995). We applied Spearman's rank correlation to compare the ordinal glare responses with the ocular parameters (Spearman, 1987). The Pearson correlation coefficient was applied to compare responses on a 10-point continuous scale with the MPOD and other measured parameters (Pearson, 1901). The strength of the correlation between the two variables was determined by Cohen's effect size thresholds (Cohen, 1988), which consider a correlation coefficient > 0.3 as a moderate effect, and > 0.5 as a strong effect. The internal reliability of participants' answers to glare questions was checked by applying Cronbach's alpha where α>0.9 presents excellent consistency between the questions.

5.3 Results

5.3.1 Final dataset

We collected a total of 275 datapoints, of which 220 were from the 55 participants in experiment I, each exposed to four experimental conditions under color-neutral glazing, and 55 from experiment II (one blue-colored glazing condition per participant). After filtering the data (cf.
Data cleaning and processing section), 18.5% of the data was discarded from experiment I and 3.6% from experiment II. Table 5-3 presents the summary of the final dataset. All the analyses presented in the following sections were performed on this dataset.

Table 5-3 Summary of data cleaning steps and the resulting dataset

Data filtering step	**Experiment I**		**Experiment II**	
	No. of datapoints	**Percentage of collected data**	**No. of datapoints**	**Percentage of collected data**
Initial dataset	220	100%	55	100%
Step 1 & 2: Unstable daylight	-19	-8.6%	-2	-3.6%
Step 3: Luminance Camera error	-10	-4.45%	0	0
Step 4 & 5: Ocular abnormalities	-3 participants (-12 datapoints)	-5.4%	0	0
Final dataset	**179**	**81.5%**	**53**	**96.36%**

5.3.2 Ocular characteristics of the participants

The MPOD levels of the participants' left and right eyes were measured in both experiments using a macular pigment screener device based on HFP. MPOD is the primary variable of interest in our study to determine its relationship with glare sensitivity under daylit conditions. In experiment I, we also measured the participants' visual acuity at low contrast for baseline measurements, their photostress recovery time to compare discomfort glare, and their mean iris thickness through Optical coherence tomography (OCT) of the retina at the ophthalmic hospital. In addition, fundus photographs of both eyes were obtained and assessed qualitatively by an ophthalmologist to exclude the participants with fundoscopic evident retinal pathologies. Table 5-4 provides a descriptive summary of all these measured parameters with their mean, median, standard deviation, minimum and maximum values.

Figure 5-7 presents the distribution of the MPOD at 1° eccentricity for the left and right eyes of the participants in experiments I and II. We applied normality tests which confirmed that the data follows a normal distribution (Shapiro–Wilk test, $p>0.05$) despite a slight positive skewness (0.29). From Table 5-4 and Figure 5-7, we can infer that the MPOD distributions between experiments I and II are similar, with a mean value of 0.49 and 0.47, respectively. The MPOD ranges observed in our study are similar to previous studies with young and healthy adults (Davies & Morland, 2004; Loughman et al., 2010b; Wilson et al., 2021). The correlation coefficient between the MPOD measurements of the right and left eye is 0.87 (Pearson correlation coefficient, $P<0.0001$), indicating excellent inter-eye predictability of the measurement device. A minimum of OS (left eye) and OD (right eye) for each participant was selected for the analysis.

Table 5-4 Summary of measured ocular parameters of the participants

Experiment	Tests	Mean	Median	Minimum	Maximum	Std. dev.
Experiment I	MPOD	0.49	0.48	0.14	0.86	±0.17
	PSRT (in seconds)	11.7	11	5	34	±6
	Iris thickness (in µm)	278	280	247	321	±19
	Acuity at low contrast	28	28	5	39	±6.6
Experiment II	MPOD	0.47	0.45	0.19	0.82	±0.16

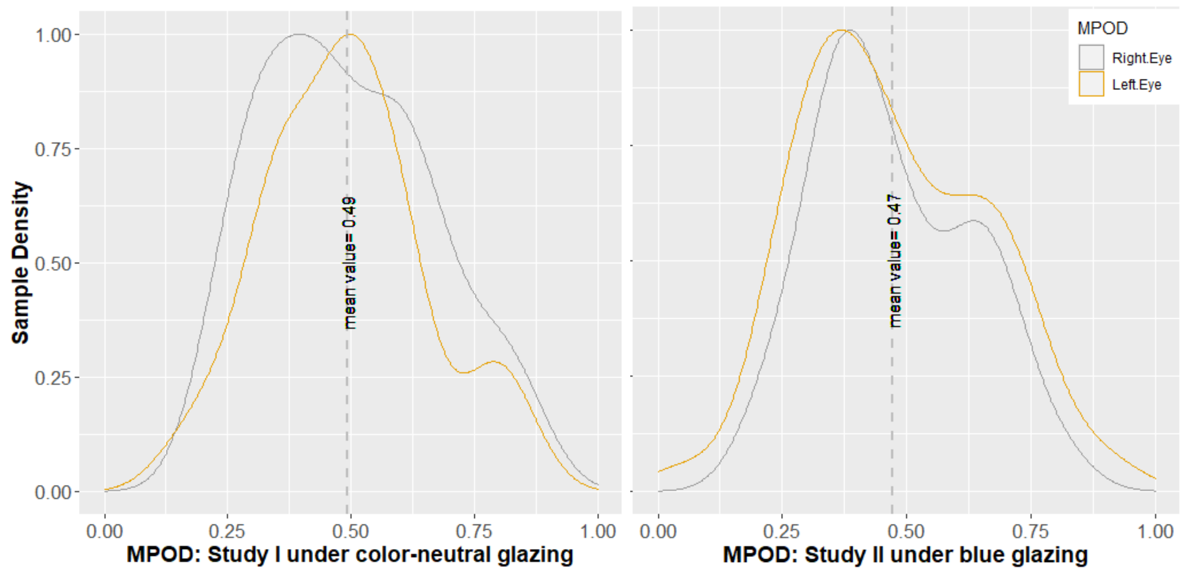

Figure 5-7 Density plots of measured MPOD values of participants' eyes in Experiment I (left) and II (right)

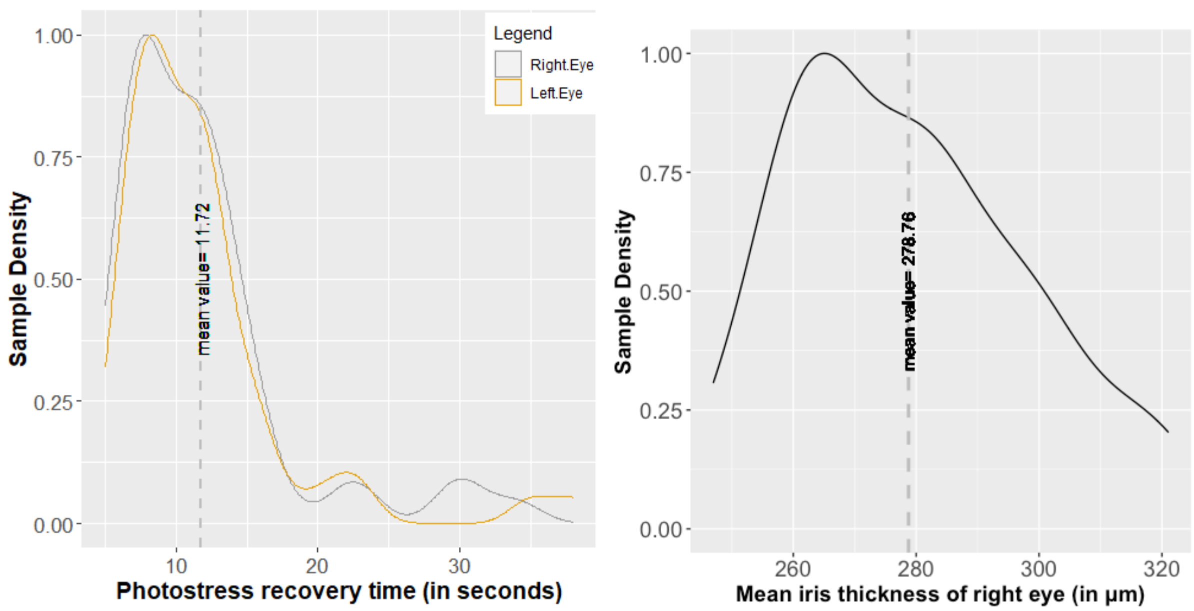

Figure 5-8: Photostress recovery time (left) and mean iris thickness of the participants' right eye (right)

Figure 5-8 provides density plots for the participants' photostress recovery time (left) and mean iris thickness (right) measured in experiment I. Photostress recovery time is defined as the time taken for visual acuity to return to normal levels after the eyes were exposed to a bright light source. From the plot, we can observe that the data is positively skewed (skewness=2.52), with a mean recovery time of 11.7 seconds (ranging from 6 to 38 seconds). These values are consistent with prior studies in which recovery times of up to 40 seconds were observed among healthy individuals (Omokhua & George, 2010; Salmon, 2019) while not contradicting another study which found a mean recovery time of only 8 seconds in a normal population but reaching 14 seconds in a diabetic population (Shrestha & Dahal, 2021) (note that diabetes was not monitored in our study but was self-reported by the participants). Iris thickness distribution, on the other hand, was measured using OCT images of the retina captured at three angles (temporal, nasal, and inferior), in each of which iris thickness was measured at 3 points to extract an overall mean value. The iris profile was also examined qualitatively on the captured images and the cases with an absence of relative foveal depression resulting in high thickness were eliminated as they might affect the macula. Finally, low-contrast visual acuity was measured using precision vision charts to ensure normal ocular health as reported in Table 5-4.

5.3.3 Discomfort glare evaluations

5.3.3.1 Photometric characteristics of the experimental conditions

Participants were exposed to four glare conditions (T1, T2, T3, and T4 in Table 5-5) for approximately 15 minutes each in randomized order under color-neutral glazing in experiment I. These four conditions differed in the transmittance of the glazing from which the sun was visible to the participants ("sun window" in Figure 5-1). Similarly, in experiment II, we created two glare conditions that differed in the transmittance value of the blue-colored glazing (B1 and B2 in Table 5-5) but each participant was exposed to only one of the two conditions for 15 minutes since the transmittance was varied between the participants. In this section, we will discuss the photometric properties of each condition shown to the participants to confirm that within each experimental condition, there was a low enough variance to consider that all participants were exposed to similar conditions within a given glazing scenario.

Table 5-5 Summary of the descriptive statistics pertaining to all experimental conditions

Study	**Scene Names**	**Sample size**	**Glazing τ_v**	**Mean E_v (lux)**	**Mean sun luminance (Millions cd/m^2)**	**Mean DGP**	**Mean CGI**	**Mean position index**	**Mean viewing angle to the sun**
Study I (Color-neutral glazing)	T1	55	0.36%	1770	2.6	0.35	36.3	3.3	32°
	T2	55	1.25%	2200	9.8	0.44	43.4	3.3	32°
	T3	55	3.4%	3300	28	0.55	49.7	3.3	32°
	T4	55	4.8%	4800	46	0.62	51.1	3.3	32°
Study II (Blue-colored glazing)	B1	27	0.39%	1130	3.6	0.38	38.2	3.2	31°
	B2	28	2.25%	2300	21.2	0.50	45.6	3.3	32°

Table 5-5 presents a summary of the descriptive statistics applied to data collected during the two experiments. These include data derived from High Dynamic Range (HDR) images that were captured at the participant's eye level and processed to derive glare source (sun) luminance, vertical illuminance at eye, discomfort glare models (CGI and DGP), position index of the sun with respect to observer and the viewing angle between the sun and the observer. They also include measured visible light transmittance (τ_v) of the glazing from where the sun was visible to the participants ("sun window"). It can be observed from Table 5-5 that the position index and the viewing angle between the sun and the observer have similar mean values across experimental conditions and two studies, which indicates that we were successful in maintaining similar a sun position in the participants' field of view. The mean values of the photometric properties of the test conditions are increasing from T1 to T4 and B1 to B2 due to the increase in the glazing transmittance allowing more daylight into the space.

Figure 5-9 shows the distribution of sun disk luminance (cd/m^2) as boxplots for four conditions under color-neutral glazing and two conditions under blue-colored glazing. We can observe that, unsurprisingly, the sun's luminance increases as a function of window transmittance and that the luminance conditions experienced for each scene overlap very little, which was our goal. This indeed ensured that participants were exposed to different levels of glare, thereby consolidating the relative assessment of their discomfort glare thresholds. Table 5-5 also provides the vertical illuminance at eye level (E_V) for each experimental condition, which, unsurprisingly as well, directly correlates with the window transmittance.

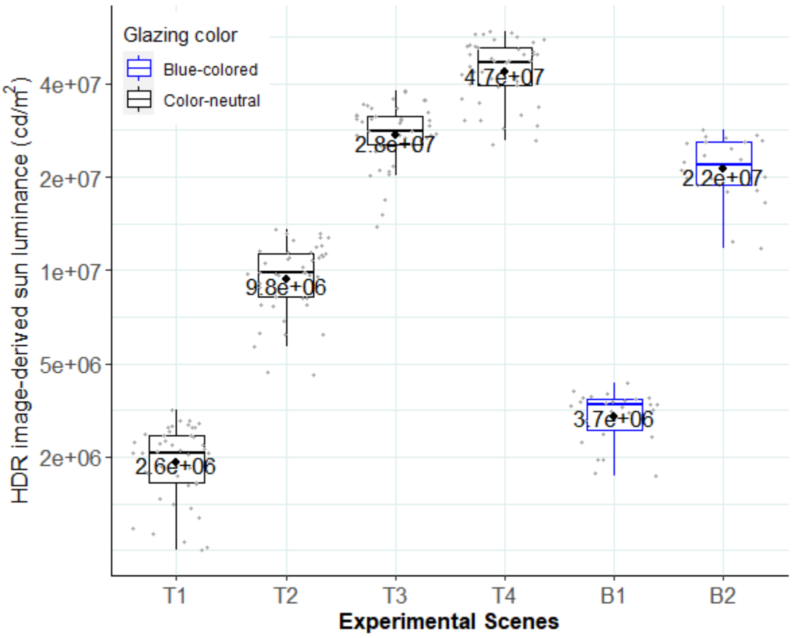

Figure 5-9 Sun luminance (cd/m^2) observed inside the room by the participants measured from HDR images shown as the boxplots with scatter for all the experimental conditions; median values are displayed and mean are indicated as the black point

Figure 5-10 presents the distribution of daylight glare probability (DGP) values, a glare metric that quantifies the contrast and saturation effects in the field of view of the observer (Wienold & Christoffersen, 2006b). Again, DGP increases as a function of window transmittance since other parameters such as the position and size of the sun remain similar between the tested conditions. The increased intensity of the sun disk elevates both the saturation and contrast in the field of view, thus increasing the DGP. The DGP cut-off value, used to distinguish between disturbing and non-disturbing glare used in the European standard EN17037, is 0.40 (Wienold, 2019). This value categorizes all our experimental conditions as creating disturbing glare except the conditions T1 and B2 where the sun window transmittance was 0.36% and 0.39%, respectively. In addition to DGP, we also measured CGI (CIE Glare Index) (Einhorn, 1979a), another validated glare model based mainly on the contrast effect. Table 5-5 shows the mean CGI values of the experimental conditions, which vary similarly to DGP values.

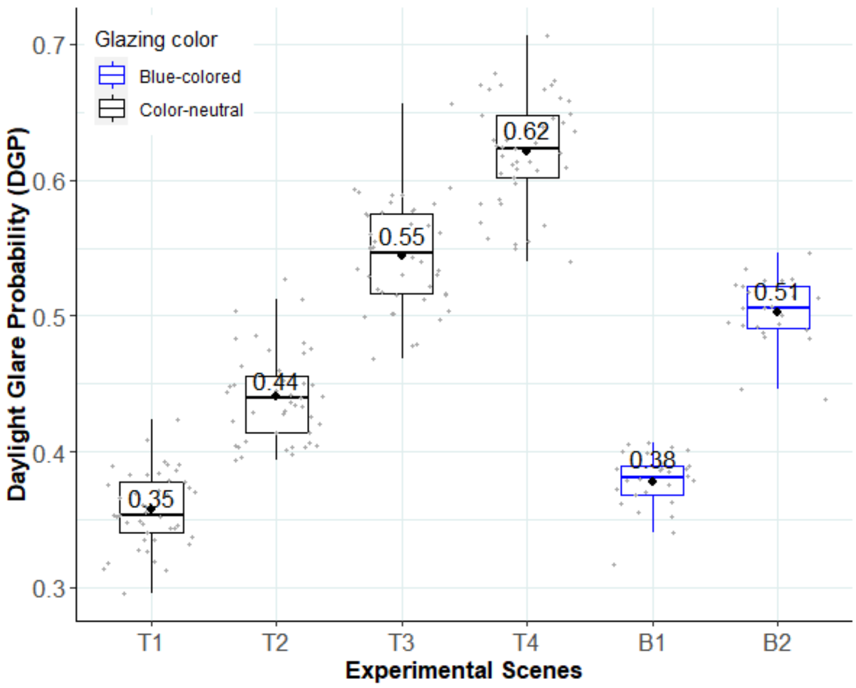

Figure 5-10 DGP values measured from HDR images shown as the boxplots with scatter with median values are displayed and mean are indicated as the black point

5.3.3.2 Participant's subjective *responses*

Participants performed a typing task while exposed to each test condition and then answered some questions (see Table 5-2) about their visual comfort during that condition. In this section, we will present the distribution of their responses to glare questions in the form of stacked bar plots. Figures 5-11 and 5-12 show the percentage distribution of glare responses from the participants, rated on a binary ''Yes/No" scale (question 2 in Table 5-2) and on a four-point scale "Imperceptible - Noticeable - Disturbing - Intolerable" (question 3 in Table 5-2), respectively. Comparing the two glare questions in figures 5-11 and 5-12, a similar trend of discomfort glare perception can be seen, indicating an agreement between the participants' responses. Furthermore, Cronbach's alpha between questions 3, 4, and 5 in Table 5-2 is 0.93, which shows an excellent inter-consistency between the participants' answers (Cronbach, 1951). In addition, we also compared the results from the glare sensitivity test conducted in electric lighting (procedure mentioned in section 5.2.3.2 and in (Jain et al. 2021)) to the glare perception reported in daylight for each participant and found them consistent with each other (r=0.71). Therefore, we decided to focus the analysis only on the glare responses received to questions 2 and 3, and eye fatigue responses on question 6 from Table 5-2, which are in fact also often used questions in discomfort glare studies (Karmann et al., 2022; Pierson, Piderit, et al., 2021; Wienold et al., 2019a).

In figures 5-11 and 5-12, we can observe that, as expected, a greater number of participants experienced discomfort from glare when the window transmittance increased. While the subjective glare responses follow the prediction indicated by glare metrics, the glare metric thresholds under color-neutral daylit conditions are consistently higher than under blue-colored conditions. In other words, participants experienced glare more strongly under the blue-colored sun, which follows previous literature and is further investigated in another article by the same authors (Jain et al., 2023). In the color-neutral conditions of experiment I, it can be seen in figures 5-11 and 5-12 that a majority of the participants switched their votes to "yes", and to "disturbing" glare, when going from condition T2 (mean DGP 0.44) to T3 (mean DGP 0.55): the glare thresholds of reporting 'disturbing' glare under color-neutral scenarios are thus higher than the ones reported in EN17037 (DGP threshold 0.40), indicating more tolerance to glare than what the DGP model would have predicted. We can also observe a rather high inter-individual variability among the participants' responses when experiencing similar lighting conditions, which once again points to different levels of sensitivity towards discomfort glare from one person to another. From the available data, we decided to group participants who answered 'Yes' to question 2 (cf. figure 5-11) and answered above 'disturbing' to question 3 in Table 5-2 (cf. figure 5-12) as more sensitive towards glare, and the rest of the participants as being less sensitive to glare. We then compared the measured MP levels between these two groups. The analysis outcomes are presented in the next section.

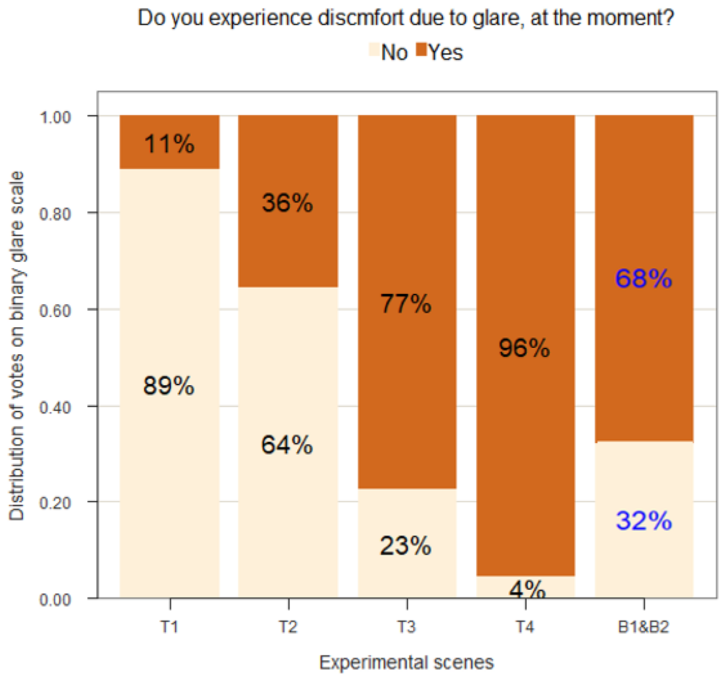

Figure 5-11 Distribution of participants' responses to discomfort glare on binary response labels

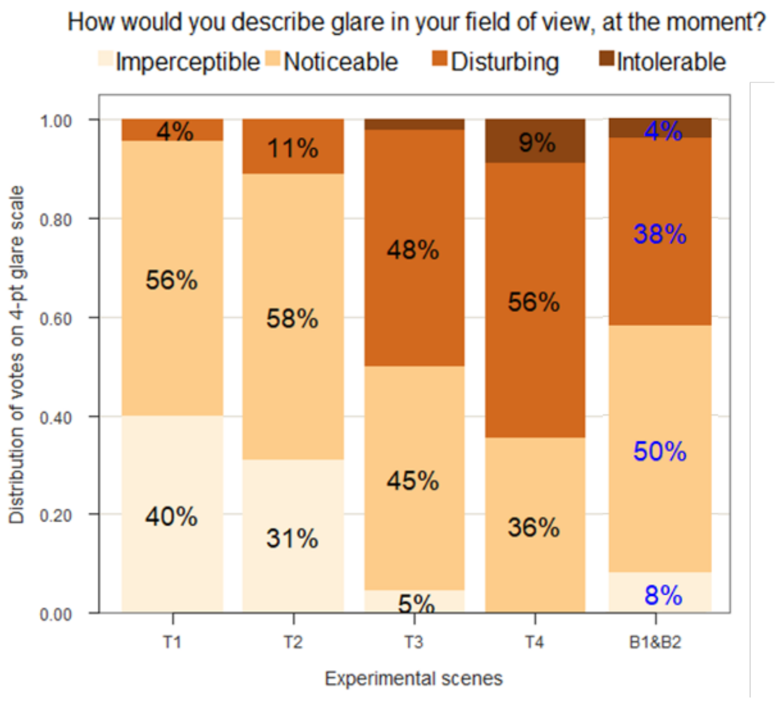

Figure 5-12 Distribution of participants' responses to discomfort glare on a 4-point scale

In parallel, we analyzed the answers to question 6 in Table 5-2, which pertained to eye fatigue, and observed a similar trend as to discomfort glare perception, i.e. that participants' eye fatigue increased with their discomfort from glare. During conditions, T3 and T4, 30% to 40% of the participants experienced moderate to severe eye fatigue.

5.3.4 Influence of MPOD on glare perception

Based on the participants' responses in both studies across all conditions and their inferred sensitivity to glare as explained above, we grouped them as more versus less sensitive to glare and then compared the measured MPOD levels between the two groups. Figure 5-12 shows the box plots of pairwise comparisons of the participants' MPOD levels between the groups who answered "Yes" and the group who answered "No" to the binary glare question. We applied Wilcoxon signed rank test (Wilcoxon, 1945) to check whether the differences in MPOD levels between the more sensitive and less sensitive groups are statistically significant. The resulting p-values are reported in Figure 5-12 and Table 5-6.

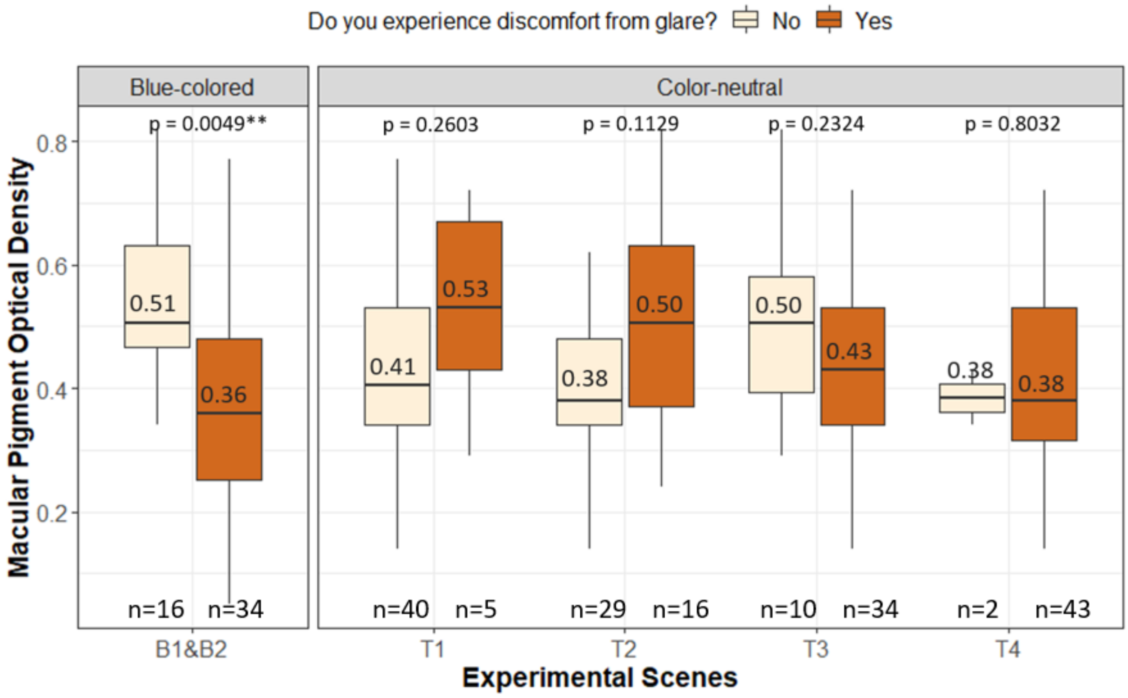

Figure 5-13 Box plots comparing the mean differences of MPOD between the two groups of participants experiencing glare and not experiencing glare under blue-colored and color-neutral glazing.

None of the groups under color-neutral lighting conditions have statistically significant differences (at $\alpha=0.05$) in MPOD levels (figure 5-13). In conditions T1 and T2 we can observe, although not statistically significant, slightly higher MPOD among the group reporting glare compared to the group not reporting glare, whereas the reverse is true for condition T3. These results do not seem consistent with what most of the literature seems to indicate, i.e. that participants with higher MPOD experienced less visual discomfort under neutral electric lighting settings (Hammond et al., 2001a, 2013; Stringham et al., 2011b). It should, however, be noted that the number of data points in one of the two groups under T1 and T4 conditions is very low ($n\leq5$) (figure 5-13). This can make the results less reliable in these two conditions due to the test statistics not properly following a $\chi2$ distribution (McDonald, 2009). We thus focused on conditions T2 and T3, which have sufficient datapoints to draw results but did not observe a statistically significant effect of MPOD on the participants' glare sensitivity under color-neutral daylit scenarios.

In contrast to color-neutral conditions, we observed a significant difference (p-value<0.05, effect size=0.40) in the MPOD levels associated with each group under the blue lighting conditions: participants who reported discomfort glare were found to have lower MPOD levels than the participants who did not report glare under blue-colored daylit conditions (cf. figure 5-13). We found significant results with an effect size of 0.40 indicating a moderate effect of MPOD on glare sensitivity following Cohen's effect size threshold (Cohen, 1988). Participants with denser macular pigments were better able to tolerate the glare from the sun filtered through the glazing exhibiting a blue color. This finding is unexpected since in our study glare source is not close to the fovea where macular pigments are most concentrated. In literature, studies that found an impact of MP on visual discomfort always had the glare source close to the fovea. Therefore, it can be hypothesized that in our study participants' free gaze behaviour unlike past studies might have caused instances where the sun was in fact close to the fovea.

Similar findings came from the correlational analyses between MPOD and glare perception, presented in Table 5-7. The correlation coefficients are again shown as being significant with a moderate effect size only in the case of blue-colored daylit scenarios, while they remain non-significant in color-neutral scenarios.

Table 5-6 Results of the Wilcoxon rank-sum test assessing the statistical significance of the MPOD differences between the glare-sensitive and non-sensitive groups

Response group	**Experiment**	**Experimental scenes**	**Wilcoxon, p-value (Bonferroni corrected)**	**Effect size**
Yes/No	Experiment I (Color-neutral glazing)	T1	0.260	0.17
		T2	0.113	0.24
		T3	0.2324	0.18
		T4	0.8032	0.04
	Experiment II (Blue-colored glazing)	B1 & B2	**0.0049****	**0.40**

5.3.5 Influence of other measured ocular characteristics on glare perception

In addition to MPOD, the participants' photostress recovery time and iris thickness were also measured in experiment I under color-neutral daylit scenarios. Though the effect of photostress recovery time or iris thickness on discomfort glare has not yet been explored in previous research, some studies (Stringham et al., 2011b; Wenzel et al., 2006a) have tried to relate them to macular pigmentation and found that patients with a higher pigment density did seem to have a shorter recovery time; iris thickness, however, was only found to weakly correlate with denser macular pigments. Based on these findings, we formulated the hypothesis that participants with shorter recovery times and denser iris would be better able to tolerate discomfort glare.

Table 5-7 Correlation coefficients between participants' subjective responses to glare and their measured ocular parameters

Subjective Response type (cf. Table 5-7)	**Correlation metric**	**MPOD**		**Photostress recovery time**	**Iris thickness**
		Blue	**Neutral**		
Binary (question 2)	*Point-biserial*	**-0.40***	0.27	0.04	0.22
4-point (question 3)	*Spearman's rank*	**-0.38***	0.28	0.08	0.21
4-point Eye strain (question 6)		-0.07	0.11	-0.18	0.16

From Table 5-7, we can infer that both photostress recovery time and iris thickness have no statistically significant ($p>0.05$) association with glare perception, independently of the question used to assess it. Additionally, eye strain (question 6, Table 5-2) was not found to correlate with any of the measured ocular parameters as shown in Table 5-7. To further confirm whether our hypothesis was disproved by our study's outcomes, we also conducted a further pairwise comparison on both recovery time and iris thickness between the sensitive and non-sensitive groups defined previously. We again did not find any significant differences between the two groups (Wilcoxon $p>0.05$) though we did find a moderate correlation between photostress recovery time and MPOD (Pearson's rho=0.40), as would be expected based on literature (Hammond et al., 2013; Stringham et al., 2011b).

5.4 Discussions

Unlike most past studies, we did not find an influence of macular pigments on discomfort glare perception under neutral daylit conditions. One potential explanation could be that the glare source was not restricted to the fovea in our study (mean viewing angle 32°), whereas in previous studies the sources were within at most 6° of the participants' central line of sight. Another explanation could be that daylight filtered by neutral glazing was of a broad enough spectrum not to be dominated by short wavelength radiation, and that this was not the case in most of the previous studies that used a shortwave-dominated xenon lamp. To investigate the second explanation further, we exposed participants to red, green, blue, and color-neutral tinted glazing in experiment II and found a significant correlation between the MPOD and participants' glare perception only with the blue glazing, whereas like in experiment I, this correlation became non-significant with the other glazings. Therefore, our findings highlight that the spectral composition of the glare source plays a key role in determining the extent to which macular pigments can contribute to discomfort glare protection. Although the color-neutral filters we used in our study had relatively higher transmission under shorter wavelengths compared to regular non-tinted glazing (as shown in Figure 5-4), their transmission was not as high as the blue-colored filter that had peak transmission at 440nm, which is strongly absorbed by MP. This indicates that an influence of MP on glare protection would presumably only be seen when using a glare source dominated by short-wavelength radiation.

Another important point relates to the fact that our participants were free to look around, unlike in previous studies. Gaze behavior should thus be looked at more carefully in our study. The mean viewing angle between the sun and the participants' central line of sight (when looking at their monitor screen) was about 32° in the vertical plane, and we estimated that over the course of each experimental session, the participants' average gaze direction varied from +10 degrees to -15 degrees based on the recording of their faces during the exposure processed in a deep learning model (Baltrusaitis et al., 2018). This gaze behavior indicates that even though the glare source (sun) was not projected in the fovea, there may have been instances where the sun was closer to the fovea and therefore, where the attenuation through the macula may have been stronger. Looking at other studies with relatively free viewing conditions like Stringham et. al (Stringham et al., 2011b), which did find a strong inverse correlation between glare ratings and MPOD ($\rho=-0.60$) had used a LED to create glare with a narrow emission spectrum and a large peak at 440nm and had glare source projected at central 5° of subject's retina, which are the main differences from the present study. We hypothesized that a smaller viewing angle between the sun and participants' retina could result in a stronger impact of macular pigments in protection against glare from the sun.

One limitation of note in our study, common to many studies conducted in university environments, is that its outcomes are based on young healthy adult participants, that were between 18-30 years old, which is not representative of a general workplace population. Therefore, the results should not be extrapolated to individuals of higher age groups and/or with certain eye pathologies. As the literature indicates that age-related macular degeneration can impact the visual function in older populations (bennett, 1977; Berendschot & van Norren, 2005; Curcio et al., 1996; Flannagan, 1999a; Hammond et al., 1998), it cannot be excluded that it may also affect glare sensitivity. On the other hand, it should be noted that the findings from this study are also only valid for the daylit conditions (and spectra) and for the viewing positions relative to the window that was actually experienced by the participants and should not be generalized at this stage. Another aspect worth noting about our study is that, as a result of the rather strict exclusion criteria set for study participation and subsequent post-recruitment discarding of data associated with ocular abnormalities, we ended up with a population sample exhibiting a greater homogeneity compared to past studies, which may conceivably influence some of our study's outcomes.

Overall the findings demonstrate that MPOD cannot account for the inter-individual variability in discomfort glare perception found in normal working scenarios (i.e. with free gaze behavior, glare source outside the fovea) under neutral daylight conditions, but possibly can, in part, explain the variability when glare is perceived under saturated blue colored glazing even when the source may not be in the fovea. This finding should be further confirmed under EC glazing that exhibits blue color and is more widely used in buildings compared to the saturated blue glazing used in our experiment.

The findings also provide a deeper understanding of the role of macular pigments in discomfort glare mechanisms. Additionally, the results can also be useful for deriving prospective visual comfort models based on eye physiology for which it might be necessary, to increase their reliability and accuracy, to include individual macular pigment density when the glare sources are close to fovea and exhibit a dominant emission in the shorter wavelength region.

Acknowledgement

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Key outcomes of this study are:

- Neither macular pigment nor any other investigated ocular factors related to the macula found to have an influence on the discomfort glare perception from the sun disc filtered by color-neutral glazing in the near peripheral field of view (<30°).
- However, when exposed to sun disc filtered by blue-tinted glazing in the near peripheral field, participants with higher MPOD were better able to tolerate the glare.

The learnings from this study, that relates to the upcoming part on color and discomfort glare interactions are:

- Some of the variability in perception of glare from a blue colored glare source can be partly imputable to the variability in macular pigment density.
- The spectrally and spatially selective properties of macular pigment should be taken into account, particularly, when considering free gaze behaviors.

PART III: COLOR OF DAYLIGHT & DISCOMFORT GLARE

Chapter 6

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

Chapter 7

Perceived glare from the sun behind tinted glazing: Comparing blue vs. color-neutral tints

Chapter 8

Influence of color of daylight filtered by colored glazing on discomfort glare

Chapter 6

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

Objectives

The objectives of the study presented in this chapter are threefold:

1. To evaluate the performance of blue electrochromic (EC) glazing technology in minimizing discomfort glare when the sun disc is in the field of view of the observer.

2. To evaluate the performance of glare metrics in such scenarios i.e. with the sun in the field of view.

3. To establish an experiment protocol that minimizes the potential experimental biases by carefully considering the design parameters based on suggestions from the past studies (Allan et al., 2019; Fotios, 2009, 2015; Royer et al., 2022).

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

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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 4.8M 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).

Keywords: Discomfort glare, electrochromic glazing, user assessment, daylight

6.1 Introduction

A considerable number of studies published in recent years have proven the benefits of daylight and view out in indoor spaces for building occupants (Heschong et al., 2002; Peter Boyce et al., 2003). Windows in workplace environments providing access to sunlight and outside view have been associated with alleviated stress at work (Leather et al., 1998b) and improved productivity (Leaman & Bordass, 1999). Research in this area has greatly impacted standards and guidelines in defining the recommendations for daylight availability, visual comfort, and view out (CEN, 2019; Mardaljevic et al., 2009).

Windows and shading devices play a key role in allowing sufficient daylight into the building and providing a view of 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 of 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 (Jakubiec, 2018). Electrochromic glazing (EC) has a big potential market in such settings with large glass façades for their ability to modulate daylight in the buildings in addition to their energy-saving capabilities (EU Commission, 2003).

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 color 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 (CIE, 1983b). 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) (Hopkinson, 1972), the Predicted Glare Sensation Vote (PGSV) (Iwata & Tokura, 1998), the Unified Glare Rating (UGR) (CIE Technical Committee, 1995), the CIE Glare Index (CGI) (Einhorn, 1979b) and the Daylight Glare Probability (DGP) (Wienold & Christoffersen, 2006a), typically quantify glare by examining the human field of vision. Further, glare metrics can be divided into 3 categories (Wienold et al., 2019a): 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).

$$Discomfort\ Glare = f\,(L_s\,,\,\omega)\ /f(L_b\,,\,P). \quad (1)$$

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(Wienold, 2009)) is an often-used metric of this category (Andersen & Kleindienst, n.d.; Chaloeytoy et al., 2020; Konstantzos & Tzempelikos, 2014). 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(Jakubiec & Reinhart, 2012; Wienold et al., 2019a) and has been adopted as glare metric in the European standard "daylight in buildings" EN17037 (CEN, 2019).

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 (M. B. Aries et al., 2010), which can affect one's perceived level of productivity (Day et al., 2019b). 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 (Moeck et al., 1996a). Lee and DiBartolomeo conducted in-situ measurements on a large-area EC window of τ_v between 11% to 38% (E. S. Lee & DiBartolomeo, 2002). 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 (E. S. Lee et al., 2006). 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 (Piccolo & Simone, 2009). 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 (Piccolo et al., 2009). 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 (Ajaji & André, 2015).

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) (Clear et al., 2006b). 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 (Zinzi, 2006). 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 (Page et al., 2007). 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 (E. S. Lee et al., 2012). 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 (R. Kelly et al., 2013; R. E. Kelly et al., 2013). 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 (Day et al., 2019b). 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.

6.1.2 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.

6.2 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.

6.2.1 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 (Charness et al., 2012).

The desired sample size was derived from a power calculation in Gpower calculator tool 3.1.9.4 (Faul et al., 2007) 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 color vision, no other visual impairment such as cataract, age group between 18 to 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).

6.2.2 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 6.55m deep, 3.05m wide and 2.65m high and allowed direct contact with the outside environment (Figure 6-1). 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 (Figure 6-1 (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 (Figure 1c)). 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.

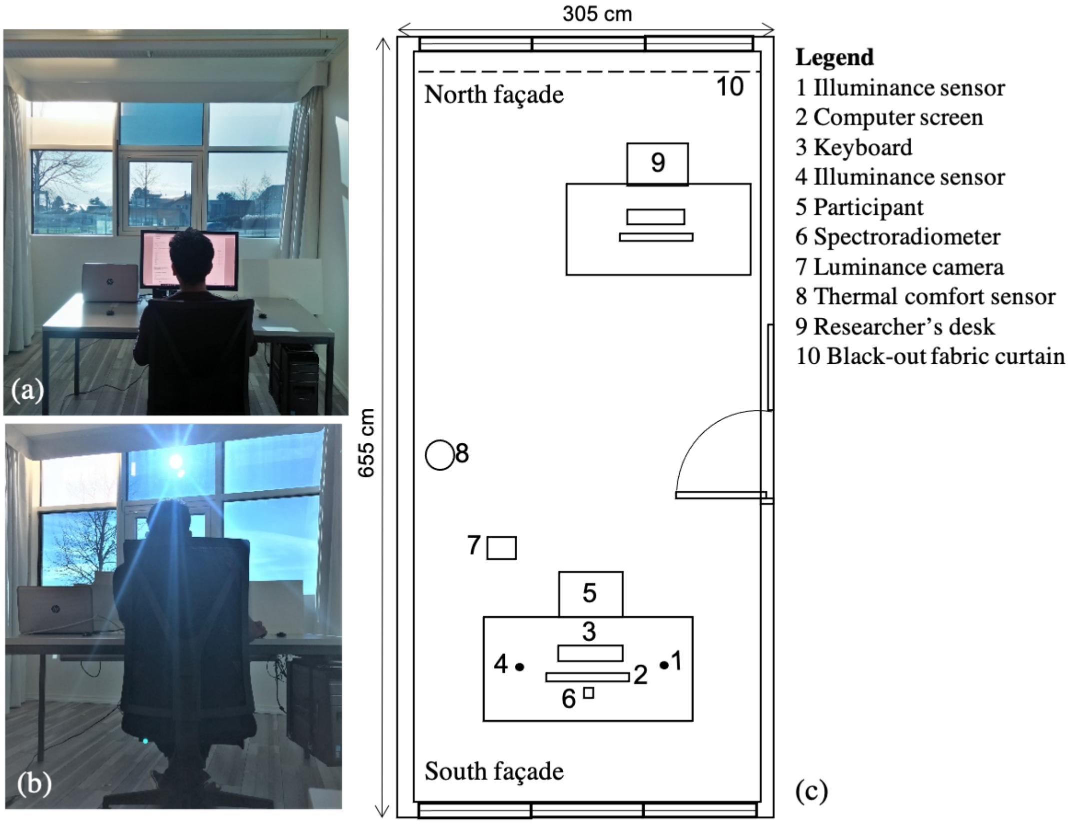

Figure 6-1 (a) and (b) Participants performing the experimental task in the test room in one of the example cases, (c) Test room layout

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 Figure 6-1(c). The participant's desk was equipped with four Hagner Special Detector SD2 to measure continuously the illuminance at 10 seconds 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.

6.2.3 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 Figure 6-2:

- The lowest switching state (nominal $\tau_{v,\,n\text{-}h}$ =0.9% according to the manufacturer)
- A switching state slightly higher than 1) (nominal $\tau_{v,\,n\text{-}h}$ =2% according to the manufacturer)
- 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 $\tau_{v,\,n\text{-}h}$ =0.22%)
- 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 Figure 6-2.

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 (R. Steiner et al., 2005) and measurement uncertainty of a $\tau_{v,\,n\text{-}h}$ measurement is less 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 6-1.

Table 6-1:Nominal, and mean measured visual transmittance of the glazing

Nominal $\tau_{v,\,n\text{-}h}$	**Mean measured $\tau_{v,\,n\text{-}h}$**
0.2% (fully tinted + additional filter)	0.0014+- 0.0002
0.9% (fully tinted)	0.6%
2%	1.6%
5.5% (view window)	3.7%
59% (fully bleached)	56%

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

6.2.4 *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 Figure 6-2), 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 Figure 6-2) was kept in the bleached state ($\tau_{v,\ n\text{-}h}$ = 56%) to limit possible color rendering problems in the room and to keep the minimum illuminance level within 300 lux 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.

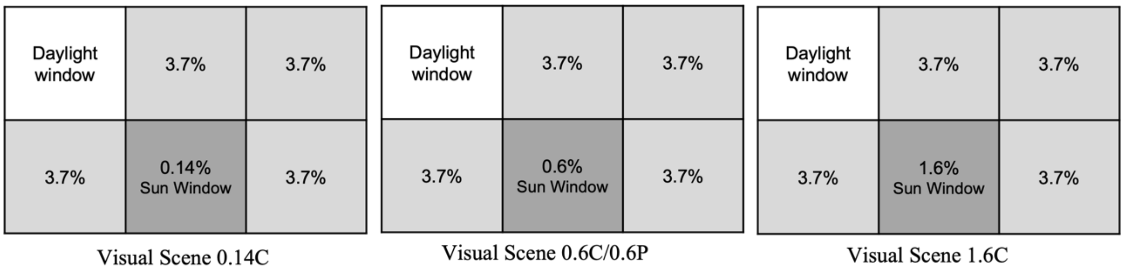

Figure 6-2 : EC glazing configuration example showing the measured $\tau_{v,\ n\text{-}h}$ values for the three levels of transmittance tested.

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 .14% and sun in the participants' central FOV

These scenarios are presented in the HDR fisheye-images shown in Figure 6-3.

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 6-3 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 minutes to switch the glazing transmittance from the highest to the lowest transmittance level and vice-versa.

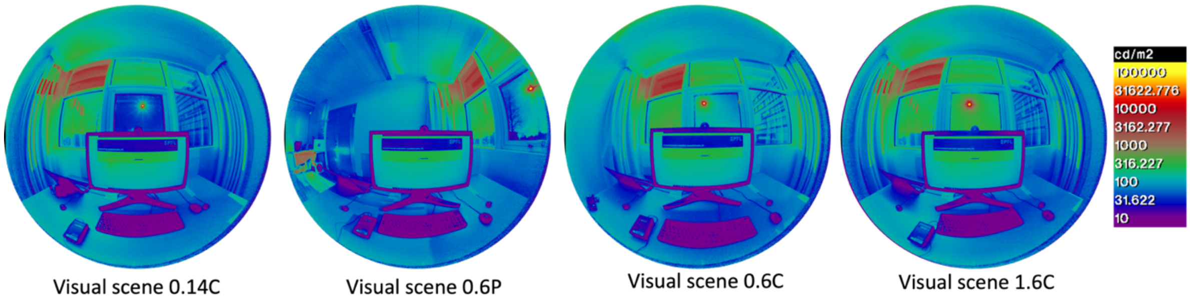

Figure 6-3: HDR falsecolor fisheye-images of four visual scenarios presented to participants

6.2.5 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 Figure 6-4. 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.

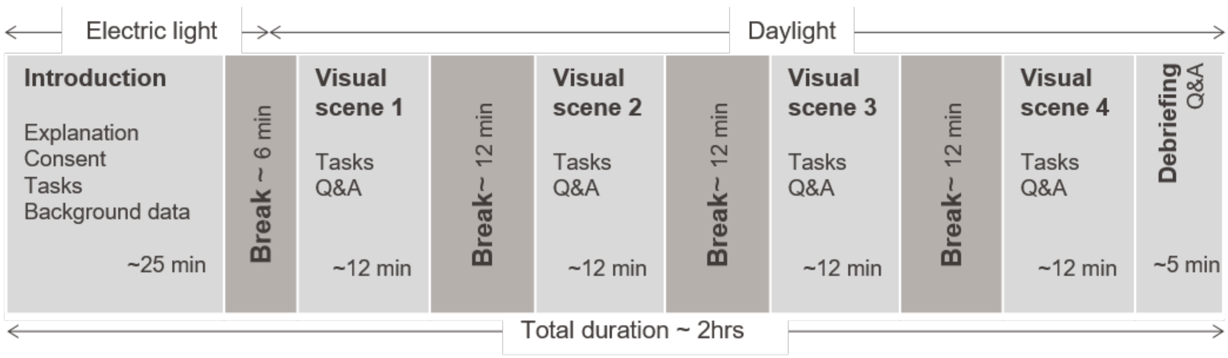

Figure 6-4: Experiment Procedure

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 pre-defined 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 (*Text Analysis Tool*, 2020)). 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 minutes (including typing task and exposure questions). The relaxation time between the scenes took also about 12 minutes, 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 (M. Kent et al., 2019).

6.2.6 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 color), 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, color 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 6-2. 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 (Allan et al., n.d.; Fotios, 2015). To address such distortions, our second question uses a binary glare scale (with *Yes/No* options) adapted from Pierson (Pierson, 2019a). 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 (W. Osterhaus & Bailey, 1992) 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.

Table 6-2: 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

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 (Pierson et al., 2018a): 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 color, self-assessed glare sensitivity, physical state, emotional state).

6.2.7 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 (Wienold & Christoffersen, 2006a) 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 to detect only the sun and to make sure it is not hidden by window frame and there is 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 2000cd/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).

6.2.8 *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 (Spearman, 1987) 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 (Cohen, 1977) 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 (Ferguson, 2009), yet, the cross-validation study on glare metrics (Wienold et al., 2019a) 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 (David W. Hosmer & Stanley Lemeshow, 2005) 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 (David W. Hosmer & Stanley Lemeshow, 2005) categorizes values > 0.7 as acceptable, values > 0.8 as excellent and Safari et al (Safari et al., 2016) describe values between 0.6 and 07 as poor. We further use Delong's test (DeLong et al., 1988) 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.

6.3 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 6.2.7, 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.

Table 6-3: Median values of visual properties and glare models of the four experimental conditions

Scene	$\tau_{v,n,n}$ (Sun window)	Sun disc luminance (cd/m^2)	Viewing angle	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

6.3.1 *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 (Garretón et al., 2015). 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 6-4. 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 6-4. 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.

Table 6-4: Descriptive statistics values for the indoor environmental parameters

	Desk illuminance (lux)				**Vertical illuminance at eye level (lux)**				**Room air temperature (ºC)**	**Relative humidity (%)**
Scene	**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

6.3.2 Discomfort glare evaluations

6.3.2.1 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 6-3 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 (
Figure *6-5* left).

Figure *6-5* (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).

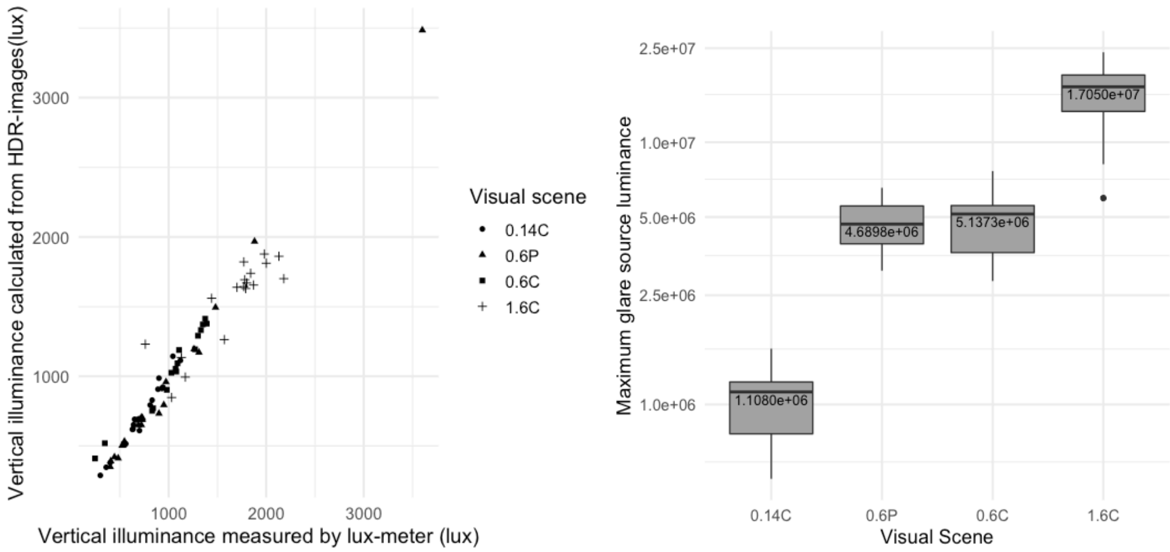

Figure 6-5 (left): Comparison of measured and image-derived vertical illuminances for different visual scenes. The RSME between the calculated and measured values is 73 lux (normalised 7%), and the normalised bias is 1.3% (corrected images were not considered).
(right): Boxplots indicating the sun disk luminance for each scenario across all tests. We indicated on each box the median value for the considered scenario.

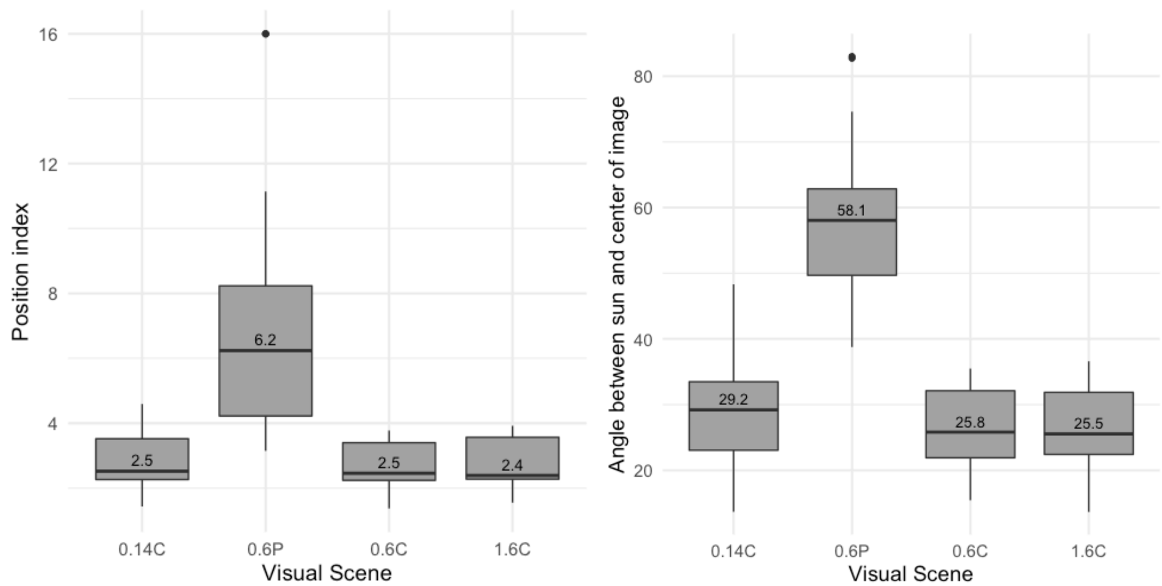

Figure 6-6 (left): Position index comparison between the four visual scenes. We indicated on each box the median values for the considered scenario,
(right): Viewing angle comparison between the four visual scenes. We indicated on each box the median values for the considered scenario

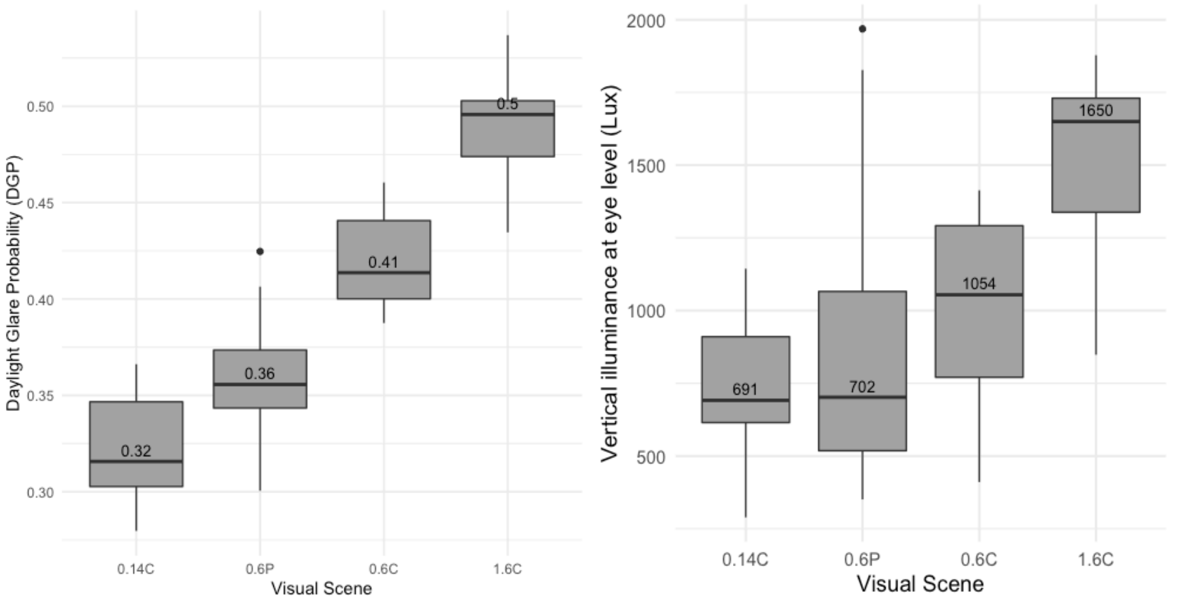

Figure 6-7 (left): Daylight glare probability values, (right): Vertical illuminance at eye level for each visual scene

Position index and viewing angle in relation to glare source in each scene category are compared in Figure *6-6* (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
Figure *6-6* (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 to 30 degrees whereas for “P” scene, it lies at 58 degrees (Figure 6-6 right).

Figure 6-7 (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 (CEN, 2019) and 0.38 as calculated in the cross-validation study (Wienold et al., 2019a). Considering these values, the median DGP values shown in Figure 6-7 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 Figure 6-7 right). As expected, E_v is not a suitable variable to distinguish the different scenes shown by the large overlap of the box plots.

6.3.2.2 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 6.2.5). Figure 6-8 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 $\boldsymbol{\tau}_{\mathbf{v,\ n\text{-}h}}$ = 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.

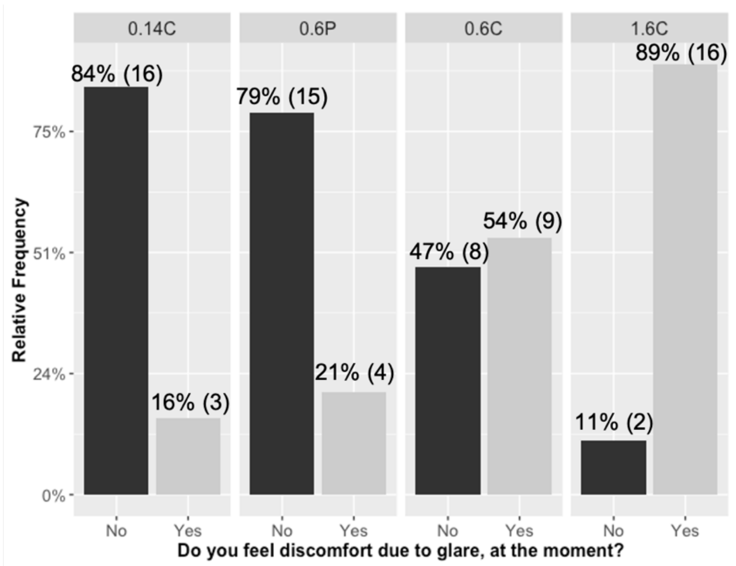

Figure 6-8: Comparison of subjective glare responses on binary scale

Similar results can be observed evaluating the subjective response on the Osterhaus four-point scale (see Figure 6-9). In addition to the fact that this scale uses four categories as response options, 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 Figure 6-9.

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 (E. S. Lee & DiBartolomeo, 2002). 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, (Westheimer, 2008) 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.

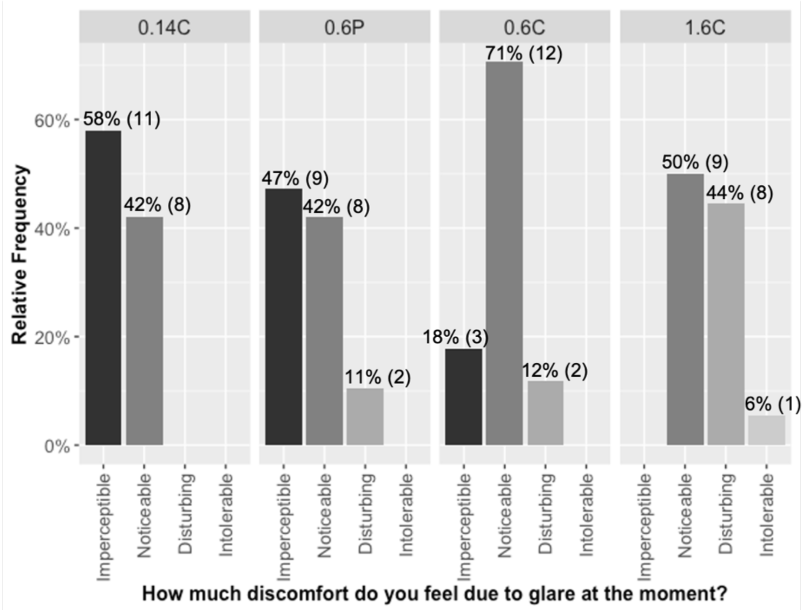

Figure 6-9: Comparison of subjective glare responses on Osterhaus scale

We also note that visual comfort could be reached with a higher glazing transmittance of the "Sun window" in case all the other 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 (Pierson, 2019a) 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.

6.3.2.3 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 (Wienold, 2004) 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.

Table 6-5: 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

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 6-6 and Figure 6-10 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.

Table 6-6: 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

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 (Cohen, 1977) 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 6-5 can be proven as significant (hittner2003 test of the cocor package [53] retains the null hypothesis with a p-value of 0.0614 for a one-tailed test). However, the Delong's test (DeLong et al., 1988) 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.

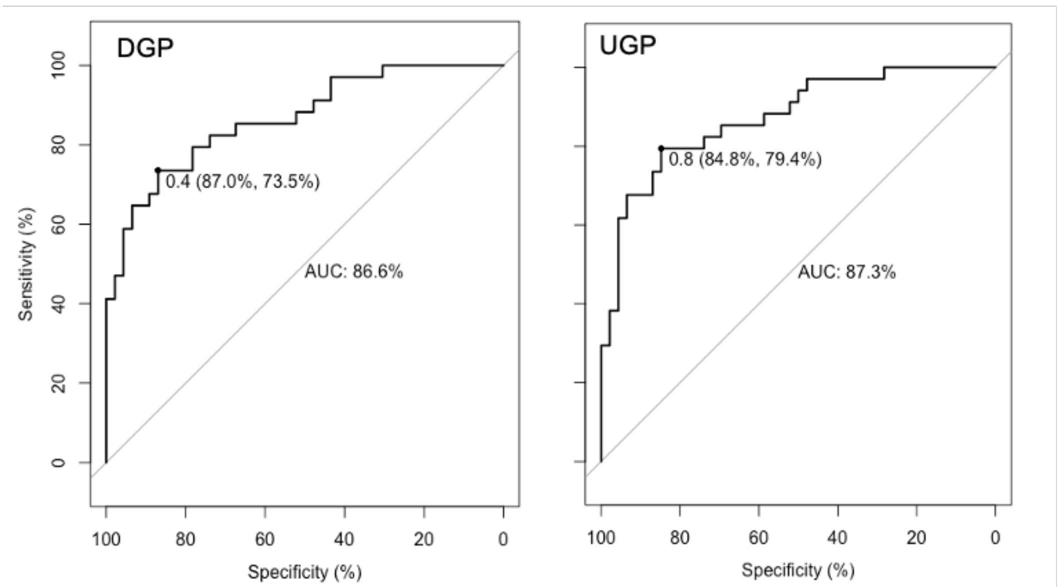

Figure 6-10: ROC curve analyses for DGP and UGP showing AUC and threshold value on the binary glare scale

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) (Wienold et al., 2019a) and EN17037 recommendations (DGP=0.40) (CEN, 2019) 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 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 (Hopkinson, 1972; Iodice, 2020; Iwata & Tokura, 1998).

6.4 Limitations

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

1. The evaluations in this study are based on young healthy adults between 18-30 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 (bennett, 1977; P. R. Boyce, 2014; Flannagan, 1999b; Iwata & Tokura, 1997) indicates, discomfort glare thresholds are expected to be lower in such cases.
2. 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 (Bujang & Adnan, 2016).
3. The exposure time to adapt to each visual scene before the start of survey questions was limited to 5 minutes. 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 (Pierson, 2019a).
4. 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.

5. Results obtained in this study are only valid for blue-tinted EC glazing and are expected to be different for other colored and color-neutral glazing due to the influence of spectrum on discomfort glare (Sivak et al., 2005; Yang et al., 2016). Earlier experiments done with colored LEDs demonstrated that colored LEDs induce more discomfort glare than white LED and among the colored LEDs blue ones gave the highest glare perception (Yang et al., 2016). We expect similar trends in daylit scenarios, although there are no such studies done under daylight so far.
6. The HDR camera used to produce luminance maps in this study implements the CIE color sensitivity function of the 2° standard observer (CIE, 1932), however, as per the literature CIE 10° standard observer function should be used to calculate luminance for parafoveal light sources (CIE publication 165:2005, 2005) that better explains the enhanced spectral sensitivity under short wavelength outside the foveal region.
7. 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.

6.5 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 $\boldsymbol{\tau}_{\mathbf{v,\,n\text{-}h}}$ 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 $\boldsymbol{\tau}_{\mathbf{v,\,n\text{-}h}}$ of 0.14% of the investigated EC glazing) was found suitable in controlling glare whereas for 16 million cd/m^2 (corresponding to a $\boldsymbol{\tau}_{\mathbf{v,\,n\text{-}h}}$ 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 0.55-0.59. 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 behaviour 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.

Acknowledgement

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Key outcomes of this study are:

- Four (CGI, DGP, UGP, and DGI) out of five evaluated glare metrics had a strong correlation with subjective glare responses (r=0.56-0.59) and were effective in predicting "glare" and "no glare" scenarios when the sun was visible behind blue-tinted EC glazing (AUC=0.57-0.84).
- A transmittance of 0.60% (equivalent to an average sun disk luminance of 5 million cd/m^2) was sufficient in controlling glare when the sun was in the peripheral FOV of the participants (median viewing angle~58°), whereas a transmittance of 0.14% (equivalent to an average sun disk luminance of 1 million cd/m^2) was required to control glare when the sun was in the central part of the FOV (median viewing angle~30°) of the participants.

Based on the experience and learnings gained from designing the experiment, we implemented the following changes to the subsequent two user studies (experiments No. 1 & 3 in Table 3-1) conducted under the scope of this thesis:

- We added four more questions on discomfort glare asked on different scales to the survey (cf. Appendix A.1). The goal was to assess the internal consistency of the answers and to further improve the reliability of the collected subjective data.
- We randomized the order of the glare questions (in total six questions) in the surveys submitted to participants in the subsequent two user studies. We should not that we actually did not find any effect of the order of questions on discomfort glare in this particular study, but this might be because we only had two questions on discomfort glare (whereas the subsequent two user studies had more).
- We increased the exposure time to adapt to each experimental condition to 8 minutes in the subsequent experiments. In the present study, the extended break time required to switch the EC glazing limited us to have a maximum possible exposure time of 5 minutes to complete the entire protocol within two hours. Although the exact time required to adapt to a visual scene is still unknown (Pierson, 2019a), 8 minutes of exposure was kept to be on the safe side.
- We increased the sample size to 55 participants in the two subsequent user studies. Since a sample size of 20 in the present EC study was barely enough to perform certain statistical analyses such the ROC curve analysis (Bujang & Adnan, 2016), and we thus aimed for a larger sample size so as to provide more power to detect a true effect, if any.

Chapter 7

7 Perceived glare from the sun behind tinted glazing: comparing blue vs. color-neutral tints

Objectives

The objectives of the study presented in this chapter are:

1. To determine whether participants' discomfort glare perception and glare thresholds varies as a result of changing the color of the sun disc (glare source) by using blue and color-neutral glazing when sun is in the field of view.

2. If the effect of color is found, we determine whether the previously proposed spectral discomfort glare models that include the effect of spectrum are able to anticipate the differences in perceived glare from blue vs. color-neutral sun disc.

Perceived glare from the sun behind tinted glazing: comparing blue vs. color-neutral tints

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Abstract

While the influence of a glare source's spectrum on sensitivity to discomfort glare has been demonstrated repeatedly under electric light conditions, it has not yet been studied under actual daylit conditions. To investigate the influence of spectral alterations of the sun disc on glare perception when seen behind a colored glazing, we performed a cross-evaluation of occupants' visual comfort in a space either daylit through blue-tinted electrochromic (EC) glazing (20 participants) or through color-neutral glazing (55 participants), having selected two types of glazing that are widely employed in commercial buildings. Under both types of glazing, participants experienced four glare scenarios presenting different glazing transmittances (from low to extremely low) in which the sun was the only glare source visible. Comparing the participants' responses to glare, we found that participants experienced discomfort more often in blue-tinted glazing compared to color-neutral glazing, even though glare metrics would have predicted higher levels of discomfort in these latter cases. This indicates that participants basically tolerated glare better under color-neutral daylit conditions compared to blue-colored conditions. To explain our findings, we considered four spectral discomfort glare sensitivity functions that have previously been proposed to replace the standard CIE $V_{2°}(\lambda)$ and applied them to the DGP and CGI glare metrics. However, none of these adjustments to glare metrics made any difference to our findings, which consistently showed an increased glare sensitivity under shorter wavelengths, indicating that its cause should be sought elsewhere. Some hypotheses are formulated at the end of the paper in this regard.

Keywords: Discomfort glare, daylight, spectral sensitivity, glazing, electrochromic technology, user assessment

7.1 Introduction

Windows in a workplace environment are desirable for their many proven physiological, psychological and economic benefits such as provision of daylight, access to outdoor views and increasing the rental value of the space (P. Boyce, 2022; Leather et al., 1998b; Turan et al., 2019). Daylight from windows can also help in improving health, productivity, and overall well-being (M. Aries et al., 2015; Heschong et al., 2002). However, daylight could also be responsible for discomfort glare which can cause occupants to block daylight out by closing the blinds for instance (O'Brien et al., 2012). Therefore, reducing the likelihood of discomfort is essential to maximize the potential of windows for adequate daylight provision. A window's glazing properties play a key role in defining the quality and quantity of transmitted daylight in a space. The switchable electrochromic (EC) glazing technology, for instance, allows to choose from a range of transmittance levels and can act as a glare protection at very low transmittance levels while still maintaining some view to the outside. Both simulation- and measurement-based analyses have been conducted in the past by research and industry groups, alongside multiple user assessment studies, to evaluate the potential of EC glazing in controlling comfort without blocking parts of the view (Clear et al., 2006a; Jain, Karmann, et al., 2022; E. S. Lee et al., 2006; Mardaljevic et al., 2016a; Moeck et al., 1996b; Paule et al., 2017).

What has been less investigated is the effect, on visual discomfort, of the spectral shift towards the short wavelength range that commercially available EC glazing material typically exhibit in their darkened state, causing them to appear blue in color and resulting in a distortion of the daylight spectrum inside the space (Baetens et al., 2010). While a few studies have looked at the effect of that shift on ipRGC-induced effects of light (Cajochen et al., 2005; Revell et al., 2006; Soto Magán et al., 2018), no study has yet focused on the effect of glazing color (or transmitted spectrum) on glare perception for colored or tinted glazing like EC glazing. In parallel, previous research conducted with electric light, mainly in the context of vehicular headlamps, has demonstrated that colored LEDs actually induce more discomfort glare than white LEDs. And among the colored LEDs, the blue ones gave the highest glare complaints (Bullough et al., 2014; Fekete et al., 2010; Flannagan, 1999b; Huang et al., 2018; Sivak et al., 2005; Yang et al., 2018). Note that since the daylit spectrum filtered through blue EC glazing is different from the one generated by blue LEDs, it is not known yet whether the higher sensitivity to glare observed with blue headlamps would hold true in colored daylit spaces with chromatic glazing.

Since multiple types of glazing – from solar-protective glazing to colored PV panels, dye-sensitized solar cells (or simply the glazing chosen to be colored for aesthetic purposes) – can alter the SPD of transmitted daylight (that is in fact also changing as a function of weather and time of day), it is worth studying the influence of a glare source's spectrum (once altered by a colored glazing) on the perception of discomfort glare. To investigate this, visual scenarios with neutral glazing should be compared to the scenarios with colored glazing that would alter the spectrum of the daylight glare source while keeping the perceived glare within similar range. We should note that recently published studies on next-generation EC materials have demonstrated that broadband modulation of spectral transmission was made possible by the incorporation of molybdenum into the tungsten trioxide thin films (WO_3:Mo), which allows to improve significantly the color-neutrality of the EC glazing in the dark state while further reducing the transmittance for glare control (Fleury et al., 2022; Lagier et al., 2021). Although these types of glazing are not yet commercially available, they offer great promise when it comes to occupant satisfaction, as visual comfort research has pointed out repeatedly that occupants generally prefer color-neutral illumination as it allows more natural looking environments (Jain, Karmann, et al., 2021; Mardaljevic et al., 2016b). Furthermore, recent studies on thermochromic windows have also indicated that blue tinted glazing were least acceptable among the occupants (Liang et al., 2018, 2021).

Based on these findings, the present study aims to compare glare responses from space occupants under blue versus color-neutral scenarios by performing a cross-evaluation of two controlled lab studies conducted in the same office-like environment under blue-tinted EC glazing and color-neutral glazing respectively. To the best of our knowledge, the present study is the only one that investigates the influence of broadband blue light source spectrum (sun disc altered through colored glazing) on glare perception in a workplace environment with daylight as the only light source.

7.2 Background

As per the definition provided by the International Commission on Illumination (CIE), discomfort glare causes visual irritation or annoyance without necessarily impairing the vision (CIE, 1983a). A majority of discomfort glare metrics quantifies glare in human visual field by evaluating photometric and geometric quantities including: 1) luminance of the glare source, 2) adaptation level (luminance of background or vertical illuminance at the eye), 3) size of the glare source, and 4) position index. In these glare metrics, photometric properties represented by luminance and illuminance are characterised by photopic luminous efficiency function V(λ), which is unanimously used in majority of the lighting applications.

7.2.1 Photometric considerations when evaluating glare

V(λ) is the spectral weighting function that defines the relative visual effectiveness of light of different wavelength (Stockman et al., 2008). It was first proposed by CIE in 1924 for 2° visual field ($V_{2°}(\lambda)$ or simply V(λ)), which continues to be the basis of all the photometric measurements (Gibson & Tyndall, 1923). Since then, there have been several revisions to the $V_{2°}(\lambda)$ function, specifically to improve the sensitivity in the short-wavelength region (modification by Judd-Vos (Judd, 1951; Vos, 1978) adapted by CIE 1988 as $V_M(\lambda)$ (CIE 086-1990, 1988)). The most recent one has been published by CIE TC 170-2 in 2015 (CIE 170-2: 2015, 2015), based on the physiologically derived cone-fundamentals by Sharpe and Stockman (Sharpe et al., 2005) as a linear function of L and M cones. Typical methods to derive V(λ) include side-by-side matching task or flicker photometry to determine relative brightness perception at the different wavelengths of the visible spectrum under constant and neutral (achromatic) adaptation (Gibson & Tyndall, 1923; Vos, 1978). V(λ) has a utility over a range of practical visual tasks for characterising luminous stimulus as reviewed by Lennie et al. (Lennie et al., 1993). However, several previous research has shown that the V(λ) function has limited applicability in conditions that fall outside those in which the function has been developed, whether these "new" conditions are: conditions involving chromatic and colored background adaptation (Eisner, 1982; Stockman et al., 2008; Swanson, 1993), conditions including large-sized stimuli (Kuyk, 1982), stimuli which are off-axis (Adrian, 2003) or long duration stimuli(Stockman et al., 2008; Stockman & Sharpe, 1999) or even age-related reduction in efficiency (Sagawa & Takahashi, 2001). Moreover, it has become well known that the spectral sensitivity of the human eye changes from the fovea towards the perifovea of the retina, which is attributed to the density of the cones and presence of blue-light filtering macular pigments in the macula (Stiles & Burch, 1959).

Most of the real-world daylight discomfort glare scenarios actually do include conditions with large field, off-axis and longer duration stimuli, and/or non-neutral adaptation, which therefore all represent conditions where the classical V(λ) falls short in predicting luminance. In addition, studies have shown that photopic luminance may not necessarily predict the brightness perception (Berman et al., 1990; Nayatani & Sobagaki, 2003; Yaguchi et al., 1993) which is closely associated with glare perception since glare can occur due to excess of brightness (Sweater-Hickcox et al., 2013; Yang et al., 2018). Previous literature has also shown several times that the iso-luminant glare sources of different SPDs and correlated color temperature create different perception of discomfort glare (Bullough et al., 2014; Fekete et al., 2010; Huang et al., 2018; Yoon & Kim, 2014). This further indicates that V(λ) might not be the correct weighting function to derive luminance in such cases. As $V_{2°}(\lambda)$ is only applicable when the light source lies in fovea and within 2° visual field, CIE has adopted an alternative function called $V_{10°}(\lambda)$, defined by Stiles and Burch (Stiles & Burch, 1959) that quantifies photopic sensitivity of eye for 10° visual fields (CIE publication 165:2005, 2005). Since oftentimes glare source lies outside the fovea, $V_{10°}(\lambda)$ represents a physiologically more accurate quantification of luminance in parafoveal field. Therefore $V_{10°}(\lambda)$ is used as one of the functions for quantifying photometry of the glare scenes in this study (see section 7.2.2, Eq. 4).

7.2.2 Influence of color on glare perception

Discomfort glare studies conducted with colored electric light sources in the context of automotive applications have shown that the color or spectrum of the glare source can influence discomfort glare perception. Flannagan et. Al (Flannagan et al., 1989b) evaluated glare response from 16 subjects for monochromatic light sources of equal illuminance at six wavelengths on a 9-point response scale and showed that the lowest glare perception was at 577nm stimulus and highest at 480nm. Another study by the same authors showed that the High intensity discharge lamps with more blue light evoked higher estimates of discomfort glare than the Tungsten Halogen lamps (Flannagan, 1999b). Similar results were demonstrated by Sivak et. al (Sivak et al., 2005), where the discomfort glare ratings were linearly related to the amount of blue content in LEDs as weighted by the S-cone sensitivity function. Bullough (Bullough, 2009) published experiments where participants evaluated glare from near-monochromatic light sources from 450nm to 700nm at 5° and 10° field, and found consistent results of higher glare perception at shorter wavelengths. The same author also proposed a new V(λ) function for discomfort glare (referred to as $V_{DG1}(\lambda)$, see Eq. 1), hypothesizing that S-cone response have a higher contribution in discomfort glare mechanism. However, this model failed to predict the data from Fekete et. al (Fekete et al., 2010) who proposed another model based on their findings. Their model includes the contribution of two chromatic channels (L-M and the (L+M)-S cone inputs) and of the achromatic channel (L+M), as shown in equation 2 with the best-fitted scaling factors. Kimura-Minoda and Ayama (Kimura-Minoda & Ayama, 2010), on the other hand, tested six colored LEDs from 459nm to 620nm of two red, green, blue, amber, white color and a tungsten-halogen bulb and found that blue LED caused most discomfort while the other LEDs produced a similarly lower discomfort. Based on their own findings, they proposed the luminous efficiency function shown in equation 3 and based on spectral sensitivities of the red-green and yellow-blue opponent chromatic channels.

$$V_{DG1}(\lambda) = V_{10^\circ}(\lambda) + 0.75S_{10^\circ}(\lambda) \quad \textit{(Eq. 1)}$$

$$V_{DG2}(\lambda) = 0.606V'(\lambda) + 0.157[1.62L(\lambda) + M(\lambda)] + 0.751[L(\lambda) - M(\lambda)] + 0.109[1.62L(\lambda) + M(\lambda) — S(\lambda)] \quad \textit{(Eq. 2)}$$

$$V_{DG3}(\lambda) = V(\lambda) + 0.578(L(\lambda) - 1.235M(\lambda) + 0.182S(\lambda)) + 0.02(L(\lambda) + M(\lambda) - 5.835S(\lambda)) \quad \textit{(Eq. 3)}$$

$$V_{10^\circ}(\lambda) \quad \textit{(Eq. 4)}$$

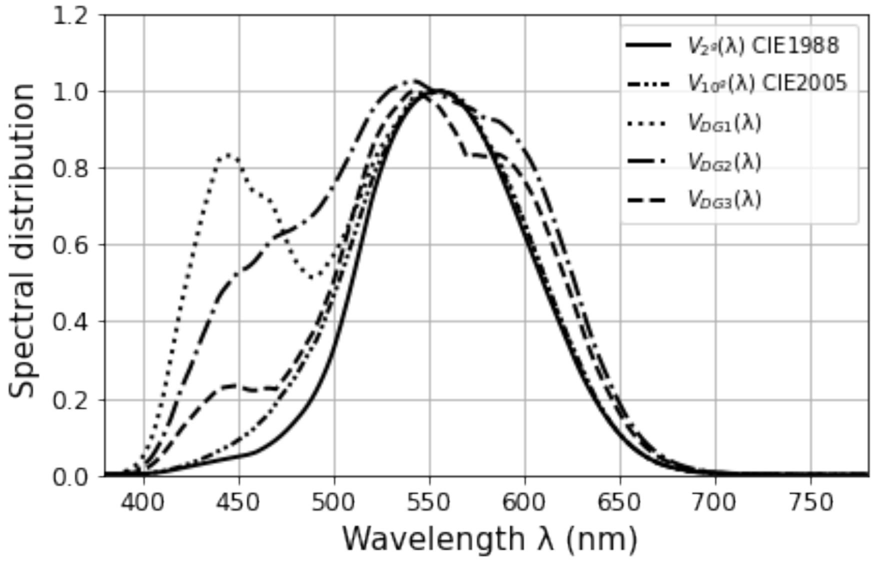

Figure 7-1 Luminous efficiency functions for discomfort glare proposed in the literature in comparison to CIE $V_{2^\circ}(\lambda)$ and $V_{10^\circ}(\lambda)$

A comprehensive review and assessment of these different photopic luminous efficiency functions has been conducted by Yang et al. (Yang et al., 2018). The authors have shown that the glare metrics based on these functions can better account for the effect of color on glare perception and work better in comparison to the Unified Glare Rating (UGR) metric (that is based on $V(\lambda)$). Figure 7-1 plots these functions across the visible range and compare them to the CIE $V_{2°}(\lambda)$ and $V_{10°}(\lambda)$ functions. It can be observed from the figure that all of these functions have higher variance in spectral sensitivities under shorter wavelength region compared to longer wavelength region.

While several studies consistently indicate the presence of an effect of color on glare perception for electric light sources, there are no studies found in literature that investigate the effect of color on one's perception of glare when dealing with daylight-induced glare sources. Furthermore, none of the daylight discomfort glare metrics have ever implemented previously proposed spectral discomfort glare sensitivity functions $V_{DG}(\lambda)$ to extend their applicability under colored daylit scenarios. To address this gap, we will investigate the effect of color on glare perception under exclusively daylit environments in office settings and compare how well glare metrics will be able to anticipate perceived glare in blue versus color-neutral daylit conditions once they have been modified based on the three $V_{DG}(\lambda)$ functions (Eq.1 to Eq. 3) as well based on the $V_{10°}(\lambda)$ (Eq. 4) compared to the standard metrics (i.e. using $V_{2°}(\lambda)$).

7.3 Objectives

This study is articulated in two phases:

1) First, we compare the glare responses and derived glare metrics thresholds from the participants survey answers under blue-tinted (n=20) versus color-neutral glazing (n=55) exhibiting different transmittances (all low). The goal is to determine whether their glare perception and thresholds varies as a result of changing the glare source's color under specific viewing position when sun is in the field of view (FOV). Two discomfort glare metrics were chosen and evaluated to derive glare thresholds: Daylight Glare probability (DGP) (Wienold & Christoffersen, 2006a) and CIE Glare Index (CGI) (Einhorn, 1979b), both identified as reliable and robust glare metrics in past studies (Jain, Karmann, et al., 2022; Quek et al., 2021; Wienold et al., 2019a).
2) If the effect of spectrum is found, we re-calculate those same glare metrics but using the four proposed spectral discomfort glare sensitivity functions listed in section 7.2.2 (Equations 1, 2, 3 and 4) and as per the method described in section 7.4.6. The idea here is to determine if any of these functions can improve the reliability of the glare metrics when it comes to anticipating how people actually perceive glare by allowing to include the effect of the glare source's spectrum.

7.4 Method

7.4.1 Experimental setup

7.4.1.1 Study Design

We cross-evaluated the data from two controlled user studies conducted in an office-like setup (Figure 7-2) with total 75 participants: the first study involved 20 participants and included blue-tinted EC glazing in the façade, the second study involved 55 participants and color-neutral glazing. The only glazed façade in the test room was south-facing. These two studies were conducted in winter months (November 2018 through March 2019 and November 2020 through March 2021) in Lausanne, Switzerland under sunny conditions to benefit from low sun angles (view was unobstructed towards the sun). Experiments were conducted for one participant at a time coming for two hours between 09:00 to 14:30. In each of the studies, participants provided their visual comfort perception under four pre-defined experimental glare conditions, each of which had the sun disc as the only glare source.

Both studies were similar in terms of study protocol and procedure, participants' demographics, experiment duration, survey questionnaires, test room and equipment settings and differed only on the following key aspects:

i) Sample size: while the number of participants differed between the studies, the lower sample size (n=20, blue EC glazing study) was still sufficient based on an a-priori analysis using G power tool (Jain, Karmann, et al., 2022); furthermore, we performed a relative rather than absolute comparison due to the imbalanced samples which allowed us to evaluate interesting statistics between the studies, further discussed in sections 7.4.7 and 7.5.3.

ii) Glazing color: the blue vs. color-neutral tint of the glazing, depicted in Figure 7-2 was the main independent variable; we investigated its effect on our dependent variable, namely glare perception.

iii) Glazing transmittance: the visible light transmittance of the glazings, provided in Figure 7-3, were initially planned to be similar between the two studies so as to only have a color variation; however, due to wrong manufacturer data, slightly higher transmittances were ultimately reached in the color-neutral glazing compared to blue-tinted glazing. In our analysis, we will therefore consider the impact of glazing transmittance as well.

7.4.1.2 Participants

Participants were university students aged 18 to 31 (mean age= 23yrs). The requirements for selection were to be in healthy conditions, have a normal color vision (tested using Ishihara and D-15 disc arrangement CVD tests (Farnsworth, 1947; Ishihara, 1917)), no other visual impairment, have a BMI within the normal range, an English proficiency level C1 or higher, not to use drugs or have an excessive consumption of alcohol, and abstain from alcohol before the experiment day. To avoid any response bias, another exclusion criterion was to be from a discipline related to the investigated field (i.e., architecture or civil engineering) or to have any link to the researchers' topic or the laboratory.

Participants were compensated as per local regulations. The project protocols were approved by the Human Research Ethics Committee at EPFL (ref. No. HREC 035-2019) and by the cantonal ethics commission of canton Vaud, Switzerland (ref. No. CER-VD 2020-00667). Table 7-1 summarizes the participants' demographics (age, gender and vision correction) for both studies: we can see that all the participants come from a similar sampling population, making the two studies comparable with each other from that perspective.

Table 7-1 Participants demographics in two studies with blue-tinted and color-neutral glazing

Study	**No. of participants**	**Age (in years)**	**Gender**	**Vision correction**
Blue-tinted	20	Min=19 Max=31 Mean=23.2	75% Male 25% Female	70% No correction 30% Glasses or lenses
Color-neutral	55	Min=19 Max=31 Mean=23	72% Male 28% Female	64% No correction 36% Glasses or lenses

7.4.1.3 Test room and equipment description

The two test rooms (one used for the blue-tinted scenarios, using EC glazing, the other for the color-neutral scenarios, using films applied on standard glazing) are shown in figure 7-2 (left and right, respectively). They are located on the EPFL campus (46°31′00.4″N 6°33′47.1″E) in Lausanne, Switzerland. During all experimental sessions, the thermal (room temperature, humidity, CO_2) and visual parameters (horizontal illuminance at desk, vertical illuminance at eye level, daylight spectrum at eye level) of the room were measured every 30 seconds throughout the experiments. Thermal parameters were kept within comfortable levels to avoid any confounding effect. We measured global (total) and diffuse solar irradiance (W/m^2) with an SPN1 Pyranometer (wavelength range: 400nm-2700nm) installed near the test room location to monitor weather conditions and utilize these measurements to define sun as described later in section 7.4.6. We used a calibrated luminance camera LMK 98-4 by TechnoTeam with a fisheye lens (type Dörr Digital Professional DHG, equidistant projection) to capture high dynamic range (HDR) images of all the experimental conditions at participant's eye position before and after their exposure to the condition. The LMK luminance camera is an absolute-calibrated Image Luminance Measuring Device (ILMD) equipped with a V(λ) filter to accurately measure the luminance of each pixel in the captured scene (Gmbh, n.d.). To capture the sun without any pixel overflow, we used Neutral Density (ND) filters ND3 (factor 1112) for blue-tinted glazing and ND4 (factor 9366) for color-neutral glazing. The ND filters provided by the camera manufacturer exhibit a nearly constant spectral transmission in the visible range. A handheld illuminance sensor was mounted below the lens of camera to compare illuminance values derived from HDR images. Images were captured using the Labsoft software available for the LMK camera. Further details about the test room and the specifics of the installed equipment can also be found in Section 2.2 of Jain et al. (Jain, Karmann, et al., 2022).

7.4.2 Experimental conditions

Each participant experienced four experimental conditions in randomized order, with the sun close to their central FOV as the only glare source, in the presence of either blue-tinted (study 1) or color-neutral glazing (study 2) without any electric light. The four experimental conditions were created by varying the transmittance of the windowpane from where the sun was visible for the participant ("sun window" in figure 7-2 and 7-3). For the blue-tinted conditions, commercially available EC glazing was resorted to, which allows the transmittance of each windowpane to be individually controlled by a digital interface (Figure 7-2 left). Whereas color-neutral conditions were achieved by attaching the color-neutral window films with low transmittances on the clear acrylic panels fixed to a double-pane glazing and these acrylic panes were manually changed during the experiment to vary the transmittance (Figure 7-2 right).

Figure 7-2 Participants performing screen-based tasks in blue-tinted glazing (left) and in color-neutral glazing (right)

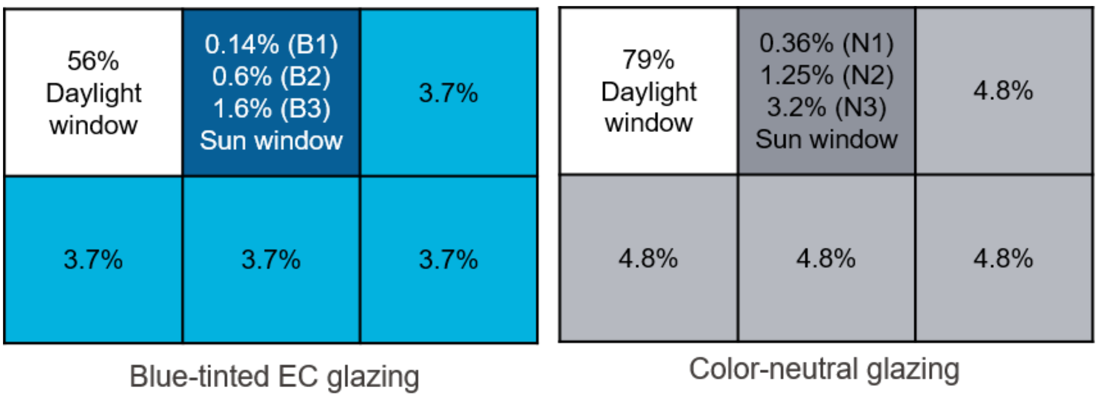

Figure 7-3 Measured visible light transmittance of the six glazing panes of blue-tinted glazing (left) and color-neutral glazing (right), also showing the transmittances of the bleached daylight window and the sun window for each experimental condition.

Participants were seated in a way to have the "sun window" always in their central field of view: to achieve this throughout the 09:00 to 14:30 time window, the participant's desk was always placed in order to face the window and was rotated as per the sun position throughout the experiment duration to maintain the same viewing direction towards the sun. We acknowledge that while this viewing direction is not recommended for office environments, it provided the most critical condition for glare evaluation, which was the point of the study. As far as the other windowpanes are concerned, one, labelled as "Daylight Window" in Figure 7-2 and 7-3, was always kept at the maximum transmittance possible for its respective façade system (EC glazing vs clear glazing) to allow sufficient daylight in the room and to minimize the effect of low color-rendering inside the room: this was a choice based on the recommendations from previous studies to maintain the neutral illumination inside the room (Mardaljevic et al., 2013, 2014, 2016b) that additionally allowed to minimize any confounding effect on glare perception that would be due to a distorted color perception inside the room (cf. section 7.5.1 for more details). The position of the "Daylight Window" itself (either upper left or upper right position) was chosen with the aim to minimize the risk of direct sun patches close to the desk. The rest of the windowpanes were kept at the same level of low transmittances within each study as shown in figure 7-3 to avoid glare from these panes.

For this article, we selected and evaluated three experimental conditions from each of the studies: the excluded condition under blue-tinted glazing is the one where the sun was in peripheral FOV of the observer and under color-neutral glazing the one where the sun window transmittance was of 4.8%. The reason for this exclusion in both cases was to ensure comparability between the two types of glazing, whether in terms of viewing direction towards the sun or too high transmittance, respectively. The three experimental conditions analyzed in this paper from each of the two studies are referred to as B1, B2 and B3 for the blue-tinted EC glazing and as N1, N2, and N3 for the color-neutral scenarios in Figure 7-3, numbered in increasing order of the sun window transmittance. These conditions are further exemplified in Figure 7-4 as falsecolor luminance images captured using the LMK camera and later processed in Radiance lighting simulation tool. It can be observed from figure 7-4 that the intensity and size of the sun is increasing as the sun window transmittances are increasing.

As our initial design intention was to keep the color-neutral and blue-tinted glazing at the same level of transmittance, we made sure to order color-neutral window films with similar transmittance values as the blue EC glazing values reported by the manufacturer. However, when confronted with our findings, we measured the spectral transmittances of the EC glazing in a professionally equipped laboratory specialized in nanotechnology and found the measured transmittance values to be substantially lower than the ones reported from the EC manufacturers, as briefly mentioned earlier (section 4.1.1). This explains the difference in τ_v values between the two experiments seen in figure 7-3.

The measured spectral transmittances of the glazings are shown in Figure 7-5. These measurements were conducted on the window test bench of the glazing and Nano-tech lab, after conducting the user study. We compared the color quality rendered by the color-neutral films (CRI 98.6) to the D65 illuminant (CRI 100) and found them very close to each other. This was done to ensure that the neutral films preserve the naturalness of the perceived colors. The measurement procedure and setup are described by Steiner et. al (R. Steiner et al., 2005). We report the normal-hemispherical visible light transmittance ($\tau_{v,n\text{-}h}$) for all the windowpanes used in our experiments in Figure 7-3. The measurement uncertainty of a $\tau_{v,n\text{-}h}$ measurement is less than 0.001 (R. Steiner et al., 2005). As shown in figure 7-3, we evaluated three levels of sun window transmittance for blue-tinted EC glazing (τ_v = 0.14%, 0.6%, 1.6%) and for the color-neutral glazing as well (τ_v = 0.36%, 1.25%, 3.4%). The top-right (or top-left, depending on the time of experiment) windowpane was kept at maximum transmittance of τ_v = 56% for blue glazing and τ_v = 79% for color-neutral glazing, to allow sufficient daylight ("Daylight window" in Figure 7-2 and 7-3). The remaining window panes were kept at constant transmittance of 3.7% for blue-tinted glazing and 4.8% for color-neutral glazing. Figure 7-5 shows the measured spectral transmittance under visible range for blue-tinted (τ_v = 1.6%) and color-neutral (τ_v = 1.25%) glazing.

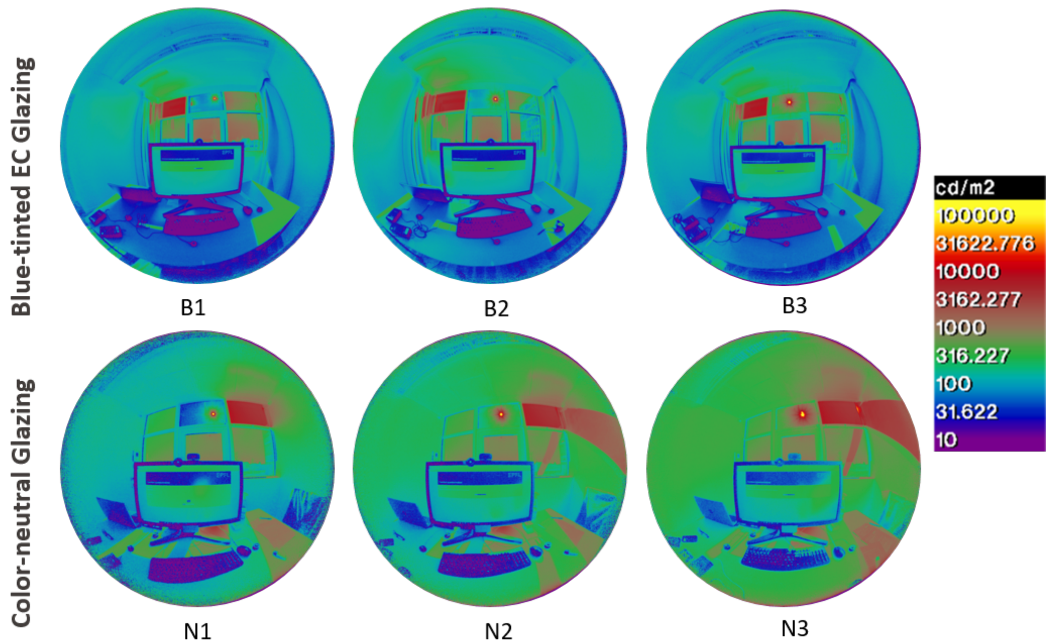

Figure 7-4 Falsecolor luminance images of the experimental conditions shown to the participants with varying visible transmittances of the sun window

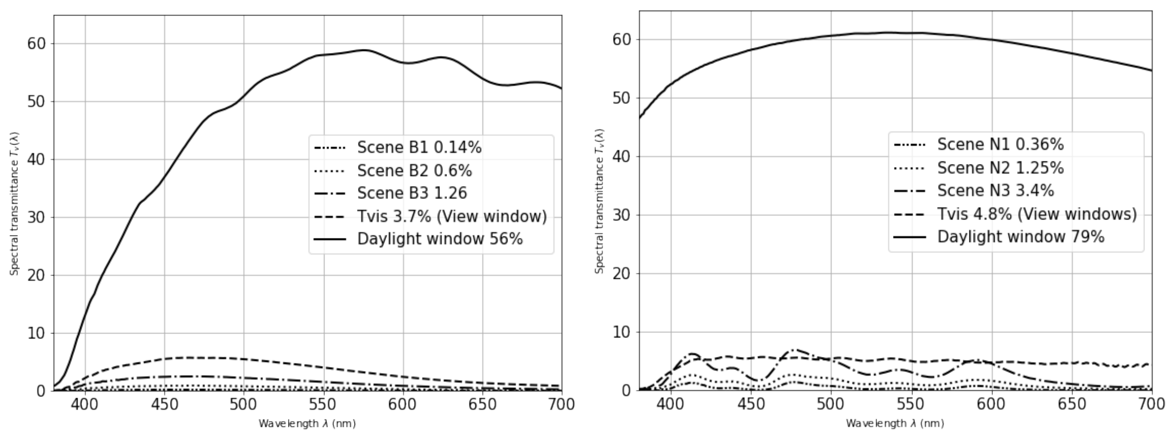

Figure 7-5 Measured spectral transmittances of blue-tinted EC (left) and color-neutral (right) glazing used in the conducted experiments

7.4.3 Experiment Procedure

After entering the test room, participants were first briefed about the experiment by the researcher in electric lighting setting with closed window shades, following a single blind procedure, i.e. , not revealing the true hypothesis of study which could potentially lead to demand characteristics bias (Nichols & Maner, 2008). After the briefing, the participants answered some background survey questions about their demographics, mood, and indoor environmental preferences. This phase was followed by a break in which the participants wore an eye mask and listened to music to allow dark adaptation, while the researcher prepared the room for exposing the participant to a first experimental condition. Each participant was exposed to four experimental conditions, experienced one by one in a randomized order to avoid anchor point bias (M. Kent et al., 2019). Under each condition, the participants performed a pre-defined typing task for about 8 minutes to allow adaption to the experimental condition and simulate an office environment. After the completion of task, they filled in an online survey reporting their level of visual and thermal (dis)comfort and satisfaction, discomfort glare, color perception of outdoor and indoor environment. Each condition was followed by a dark-adapted break. During the break, the researcher captured the HDR image of the preceding condition from the participant's eye position and measured the associated vertical illuminance value. Afterwards, the researcher changed the 'sun window' transmittance to set the upcoming condition and rotated the desk position to have sun visible through the 'sun window' close to the participant's central FOV. Following this, the HDR capture and illuminance measurements were repeated. At the end of the experiment, the participants filled out a debriefing questionnaire to report their overall experience regarding the comfort. The entire experiment lasted about two hours for a given participant.

7.4.4 Survey questionnaires

Participants answered several questions reporting their visual and thermal comfort, color perception, view out perception and satisfaction during their exposure to each condition. In this section, we detail out only the questions pertaining to discomfort glare that were asked in both the studies, listed in Table 7-2.

Table 7-2 Survey questions and their response labels pertaining to discomfort glare

Question	Response items
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
3. How do you rate the current glare from the window?	Imperceptible - Noticeable - Disturbing - Intolerable

An open-ended question (question 1 in Table 7-2) was asked in the beginning of the survey. Its aim was to allow participants to report any disturbance due to physical environment of the room without drawing attention to any specific comfort parameter such as glare, while at the same time evaluate if the participants mention glare in their answers since this was the only independent variable in the tested conditions. Questions 2 and 3 from Table 7-1, which were answered on the binary and Likert (ordinal) response labels respectively, were adapted from previous visual comfort studies (Chinazzo et al., 2018; W. Osterhaus & Bailey, 1992; Pierson, 2019b). As further analysed in section 7.5, their objective was to inform on the participants' glare perception in all experimental conditions and, more specifically, to compare the responses between the blue-colored and color-neutral daylit conditions to determine differences in glare perception owing to the influence of color.

7.4.5 Data cleansing and post-processing of HDR images

We applied specific data cleansing rules on the collected data to maximize their reliability and robustness: 1) we discarded the test cases where the deviation in measured global horizontal irradiance (GHI) was more than 25% $((GHI_{max}-GHI_{min})/GHI_{mean})$ to ensure stable weather conditions over the duration of participants' exposure time; 2) whenever the sun was hidden by the window frame or any other object within the participants' FOV (based on the visual inspection of the collected HDR images of all the test conditions), the associated data were discarded; 3) whenever the HDR images were found overexposed due to a camera error that couldn't be resolved to obtain accurate luminance maps, the associated data were discarded.

Using the LMK camera, scene images were captured in ".pf" (picture float) format and were converted to ".hdr" format which is required to run *evalglare* (Wienold, 2004) to derive photometric quantities and glare metrics from the images. All the images were analysed for pixel overflow, which was found in 20 cases for which measured vertical illuminance values were substantially higher (>25%) than the image-derived vertical illuminance values. In these cases, the associated images were corrected, rather than discarded, by replacing the overflow pixels matching the measured vertical illuminance.

7.4.6 Glare metrics derivation from the HDR images

7.4.6.1 Based on standard CIE $V_{2°}(\lambda)$

Standard glare metrics CGI and DGP based on $V_{2°}(\lambda)$ were derived from the HDR images of the experimental scene using zonal method of Evalglare (Wienold, 2004) tool in radiance lighting simulation engine. The default glare source detection method in Evalglare uses an absolute threshold of 50,000 cd/m^2, i.e., every pixel above this value is regarded as a glare source. However, applying this method will indeed lead to different sizes of glare sources (colored sun disc) seen through blue-tinted and color-neutral glazing due to the differences in the visual transmittances of glazing being tested between both cases. Therefore, to remove this bias we implement zonal calculation method in Evalglare by specifying a zone of 5.8° diameter (opening angle=0.101229, ω=0.00804651 sr) around the sun position and calculate average zonal luminance integrated over this 5.8° zone. This method would ensure that the glare sources of the same size are evaluated in the two studies, and can thus be compared. This choice of glare source size (∅=5.8°) was based on the fact that the FOV of the pyranometer measuring the DNI of the circumsolar region uses a 2.9° half aperture angle (International Association of Meteorology and Atmospheric Physics, 1986) (i.e. a 5.8° diameter too) and that ASTM G173 standards (ASTM (2020), ASTM G173, n.d.) define the standard sun spectra also for a 5.8° diameter around the sun.

Note that most of the devices measure ranges that are approximately 10 times larger than the solar disc angle (annual average approximately 0.533°). Using a 5.8° cone therefore leads to an increase of the considered solid angle by a factor of about a hundred compared to the solid angle of the sun itself (8.05e-3 sr <-> 6.797e-5 sr). Due to energy conservation, the luminance of the glare source is therefore reduced also by factor of approximately 100 – leading to a much lower impact of the sun region on perceived glare due to the proportionality between glare and log $L^2*\omega$. For that reason, the calculated thresholds for glare metrics in this study cannot be compared to other studies or to existing standards. However, since we are conducting a comparison between discomfort perception towards blue and color-neutral glare sources on a *relative* basis, the absolute thresholds are not of concern. Furthermore, there are no studies to the best of our knowledge that investigated the thresholds relevant to (or the algorithms applicable to) determining glare source sizes.

7.4.6.2 Based on additional four spectral discomfort glare sensitivity functions

Similar to standard metrics calculations, to derive the modified glare metrics, we first calculated the 5.8° zonal sun luminance weighted over four $V_{DG}(\lambda)$ functions (eq. 1 to eq. 4) that was previously discussed in section 7.2.2, made explicit in Equation 5. Since the measuring equipment used in this study employ a $V_{2°}(\lambda)$ function to measure illuminance and capture HDR imaging, a reference standard solar spectra provided by ASTM G173-03 (ASTM (2020), ASTM G173, n.d.) was used to create the sun spectrum. This sun spectrum was scaled to match the on-site measured DNI averaged over the duration of each experimental exposure resulting in E_λ used in Eq. 5. E_λ was integrated with the measured spectral transmittances (T_λ) of the blue and neutral glazing used in the six considered experimental conditions. The photopic luminance efficacy equivalent value (K_m) for α-opic functions was based on the "CIE metrology system of optical radiation for ipRGC-influenced responses to light" (CIE, 2018) and we used the libraries from the open-source "color" package in python to derive α-opic weighted glare source luminance over 5.8° zone.

$$L_{DG} = K_m \int_{380}^{780} E_\lambda * T_\lambda * V_{DG}(\lambda) d\lambda \qquad \textit{(Eq. 5)}$$

where L_{DG} is the luminance of glare source weighted by $V_{DG}(\lambda)$, K_m is the photopic luminance efficacy equivalent value for $V_{DG}(\lambda)$ function, E_λ is the scaled spectral irradiance of sun for 5.8° diameter, T_λ is the measured spectral transmittance of the glazing, and $V_{DG}(\lambda)$ is the luminous efficiency function for discomfort glare as defined in Eqs.1 to 4.

Similarly, we calculated the vertical illuminance at eye level weighted by the four $V_{DG}(\lambda)$ functions (eq. 1 to eq. 4). For calculating the direct part of vertical illuminance (E_{dir}) which is contributed solely by the sun, we followed similar approach as mentioned above for the adjusted sun luminance calculation. For the total vertical illuminance at eye level (E_v), we incorporated measured spectral irradiance profile at eye level for all the glazing configurations using the spectrophotometer data and weighted the total spectral irradiance by $V_{DG}(\lambda)$ and scaled it to match the measured vertical illuminance at eye.

These modified luminance and vertical illuminance values were used in glare equations 6 and 7 to calculate modified DGP and CGI metrics.

$$DGP\_modified = 5.87 * 10^{-5} E_{v\_DG} + 9.18 * 10^{-2} log\,(1 + \sum \frac{L_{DG}^2 \omega_{5.8°}}{E_{v\_DG}^{1.87} P^2}) + 0.16 \qquad (Eq.\ 6)$$

$$CGI\_modified = 8log2 * \frac{1+\frac{E_{dir\_DG}}{500}}{E_{v\_DG}} (\sum \frac{L_{DG}^2 \omega_{5.8°}}{P^2}) \qquad (Eq.\ 7)$$

where L_{DG} is the luminance of the glare source weighted by V_{DG} (λ)(eq. 1 to eq. 4), E_{v-DG} is the total vertical illuminance at eye level and E_{dir-DG} is the direct component of vertical illuminance adjusted as per V_{DG} (λ) (eq. 1 to eq. 4), $\omega_{5.8°}$ is the solid angle of the glare source (=0.00804651 sr), and P is the position index of the glare source.

7.4.7 Statistical methods

Descriptive statistics and boxplots were used to understand the distribution of the photometric characteristics of the experimental conditions and compare the blue-colored and color-neutral daylit conditions. We further used bar plots to compare the discomfort glare perception reported by participants under blue and color-neutral glazing.

In our analyses, we implemented two additional diagnostic tools, the ROC curves (receiver operating characteristic curve) and the PR curves (Precision-recall operative curves) to evaluate the performance of glare metrics in discriminating comfort and discomfort situations and to calculate the glare threshold distinguishing comfort from discomfort. We used a bootstrap approach for robust calculations of AUCs (area under the curve) and optimal glare thresholds, using the package *cutpointr* in R software (Thiele & Hirschfeld, 2021). Higher AUCs here indicate better prediction models: Hosmer-Lemeshow (Hosmer & Lemeshow, 2000) categorizes values > 0.7 as acceptable, values > 0.8 as excellent and Safari et al (Safari et al., 2016) describe values between 0.6 and 0.7 as poor.

A ROC curve plots the true positive rates (TPR) on the y-axis and the false positive rates (FPR) on the x-axis for each glare metric value, which varies between 0 and 1. On the other hand, a PR curve plots the positive predictive power or Precision on the y-axis (expressed as the ratio between true positives and the sum of true and false positives i.e. how good a model is at predicting the positive class) and true positive rates (TPR or recall) on the x-axis. It should be noted that PR curves tend to be more informative and robust when evaluating imbalanced datasets compared to ROC curves, which can be rather optimistic on imbalanced data with fewer samples of the minority class (Saito & Rehmsmeier, 2015).

In glare studies, the balance of binary classification data depends on the stimuli range shown to the participants and on the questionnaires used to create the binary classification. To counter this, we checked for a balance between glare and no glare cases in our dataset to implement ROC and PR curves methods accordingly. In the case of ROC curves, to obtain the optimal glare threshold, we used the point on the curve that has the minimum distance from the (0,1) i.e. the point closest to the top left corner of the curve. For the PR curves, it was instead the point closest to (1,1) or closest to top right corner of the curve that was taken as the optimal threshold. These glare thresholds were used as an indicator to compare under which glazing the participants were better able to tolerate glare. We also used the Spearman rank correlation (Spearman, 1987), a non-parametric test, to check the ability of the chosen glare metrics to predict the participants' glare discomfort votes on ordinal response labels for the given sample size.

7.5 Results

A total of 210 datapoints (60 from the blue-tinted and 150 from the color-neutral studies when including the three considered experimental conditions seen by each participant) were gathered from a total 75 participants. After applying the data cleaning rules described in section 7.4.5, we had to discard 7 datapoints from the blue-tinted study and 18 datapoints from the color-neutral study, resulting in a total of 185 datapoints (53 datapoints in blue-tinted and 132 in color-neutral glazing conditions). In this section, we will present the statistical analyses performed on the clean dataset only.

7.5.1 Spectral and photometric characteristics of the experimental conditions

In this section, we compare six experimental conditions, for which, beyond the glazing transmittance of the sun window, several other attributes have been measured or can be inferred. As shown in Table 7-3, these include: the measured vertical illuminance at the eye (E_v), the HDR image-derived sun luminance, the glare metrics DGP and CGI (calculated as per the method described in section 7.4.6.1), the position index of the glare source, the viewing angle between the sun and the observer, and the mean CCT measured at participants' eye level. Figure 7-6 plots the spectral irradiance measured at the participants' eye level with blue and neutral glazing. It can be seen from the figure that with the blue glazing, we were able to minimize the domination of the blue tint inside the room, hence preserving the naturalness of indoor elements by having the daylight window. As a result, the color inside the room were rated as natural by a majority of the participants (76%). Regarding the photometric properties, we can observe large differences between the six experimental conditions when it comes to glare source luminance or vertical illuminance at the eye – which were expected given how much the glazing transmittances differed between the conditions. We can also note that the position index (Figure 7-7) and viewing angle towards the glare source are very similar within the blue and color-neutral conditions but not between these conditions: this can be explained by the fact that the lower windowpane had to be used as the sun window (i.e. containing the glare source) in a few instances in the blue glazing conditions and a larger number of experiments happen to have been conducted with higher sun positions under color-neutral glazing, which in combination resulted in smaller position indices for the blue-tinted conditions as seen in Figure 7-6. Despite these variations in position index, it should be noted that the sun disc was consistently seen within the central FOV of the participants in all the situations.

Table 7-3 Mean values of spectral and photometric properties of the experimental conditions shown to participants

Glazing	Scene Names	Glazing τ_v	Mean E_v (in lux)	Mean Sun luminance (5.8° cone)	Mean DGP	Mean CGI	Mean Position index	Mean Viewing angle	Mean CCT at eye level
Blue-tinted EC glazing	B1	0.14%	670	9,603	0.22	19.4	2.9	29°	8627K
	B2	0.6%	1050	43,000	0.29	29.9	2.8	26°	9780K
	B3	1.6%	1650	144,647	0.38	39.0	2.7	25°	10427K
Color-neutral glazing	N1	0.36%	1770	23,600	0.27	22.3	3.3	32°	5320K
	N2	1.25%	2200	93,700	0.35	32.4	3.3	32°	5308K
	N3	3.4%	3300	271,575	0.47	41.7	3.3	32°	5372K

To validate the accuracy of the collected HDR images, the vertical illuminance calculated from the images were compared to the vertical illuminance measured using a hand-held illuminance-meter during the experiments. The scatter plot in figure 7-8 shows that the measured and image-derived E_v have a strong correlation (Pearson's r= 0.98) and the normalised RSME between the measured and image-derived values is 7%, and the normalised bias is 1.3%.

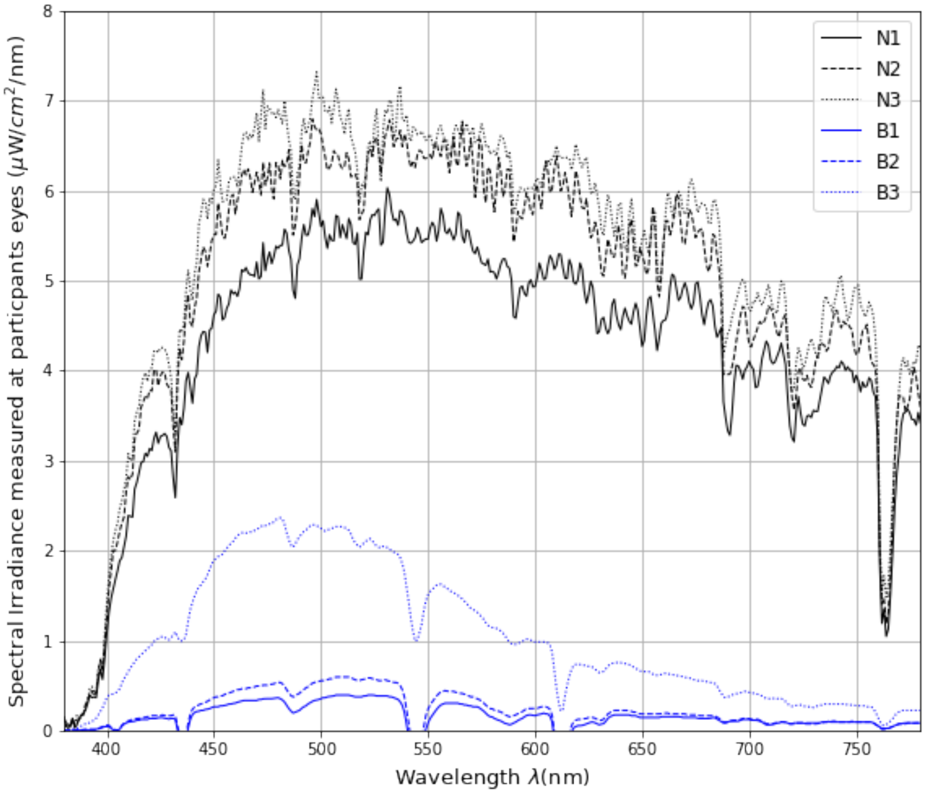

Figure 7-6 Spectral irradiance measured at participants' eye level under neutral and blue glazing

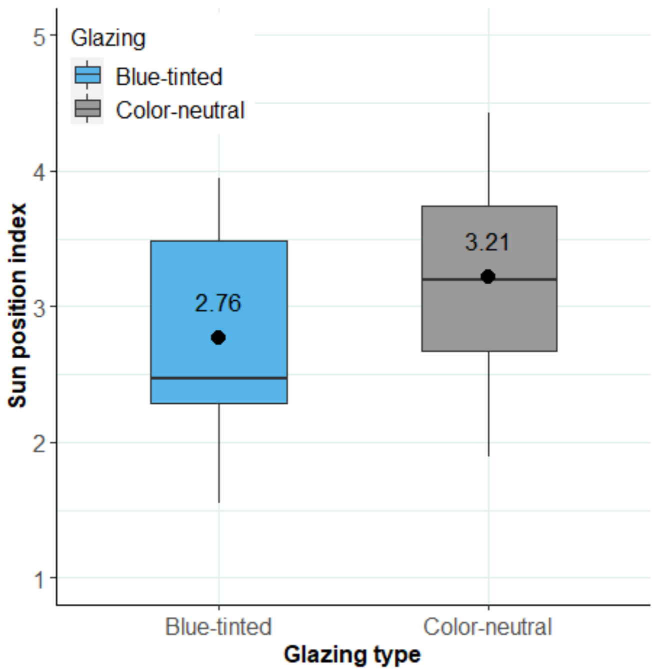

Figure 7-7 Comparison of position index between blue-tinted and color-neutral glazing

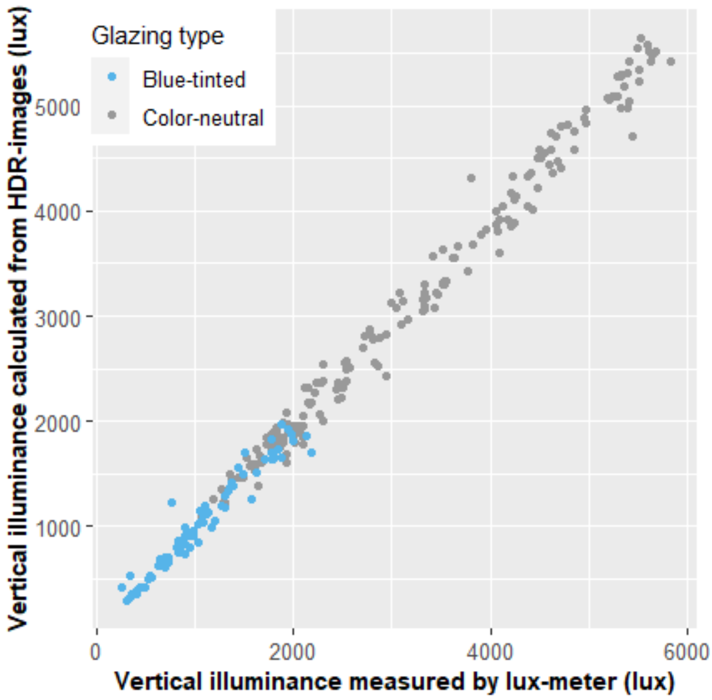

Figure 7-8 Comparison of measured and image-derived vertical illuminances between blue-tinted and color-neutral glazing.

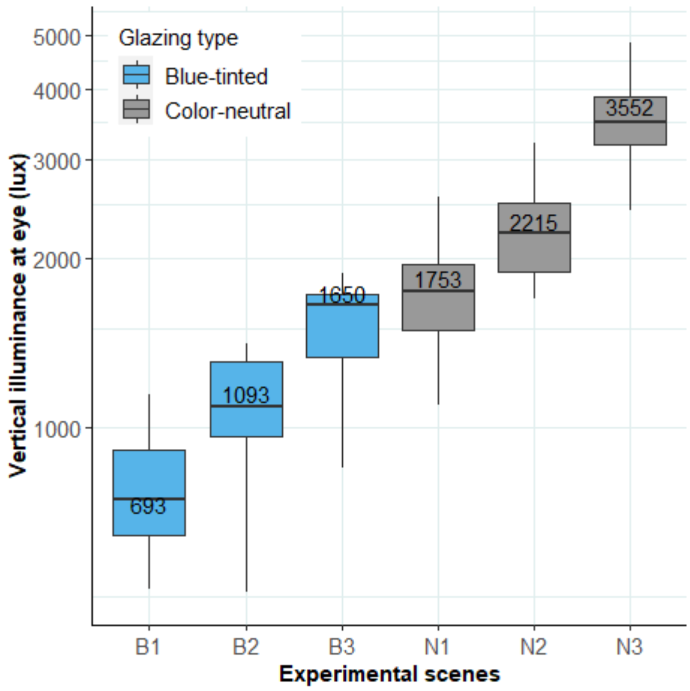

Figure 7-9 Boxplots with median values of measured vertical illuminance at eye level for all experimental conditions under blue and color-neutral glazing

Figures 7-9 to 7-12 depict the distribution of E_v, of the sun luminance over the 5.8° zone around the sun, and of the DGP and CGI metrics for the six considered experimental cases, in the form of boxplots with median values. The sun luminance, CGI and DGP values are directly proportional to the 'sun window' glazing transmittance in the increasing order of B1, N1, B2, N2, B3 and N3 experimental scenes as seen in Figures 7-10 to 7-12. We can also observe that glare metrics of all the categories have higher values in color-neutral scenarios compared to blue-tinted scenarios. While the E_v values are always higher for the color-neutral scenes compared to blue-tinted scenes and proportional to the overall glazing transmittance of all the six glazing panes combined (cf. Figure 7-9). This also indicate the inability of E_v to capture the extreme luminance of the sun and its position index in participant's FOV, and thereby making E_v less reliable as a glare metric in our study. For this reason, instead of relying on solely saturation based metrics (E_v and sun luminance), , we use contrast (CGI) and hybrid (DGP) glare metrics due to their higher predictive power and correlation with the subjective perception of glare as reported by several previous studies (Jain, Karmann, et al., 2022; Wienold et al., 2019a). When we compare blue-tinted and color-neutral conditions based on the derived DGP and CGI metric values (cf. Figures 7-11 and 7-12), we can see that blue and color-neutral cases seem to differ more when using DGP to evaluate them, due to its strong linear dependence on E_v (cf. Eq. 5), which is quite a bit higher for color-neutral cases, as shown in Figure 7-9.

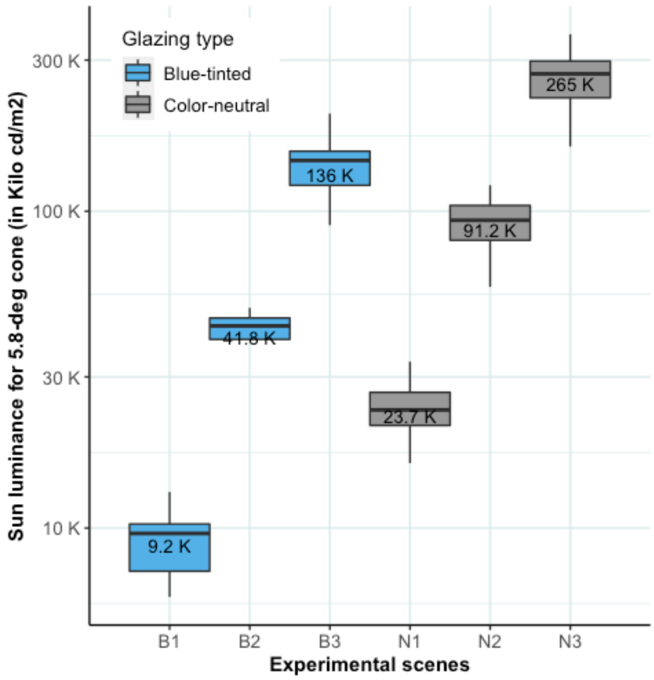

Figure 7-10 Comparison of boxplots with median values of image-derived sun and circumsolar luminance integrated over a zone of 5.8 degree around the sun between blue-tinted glazing and color-neutral glazing

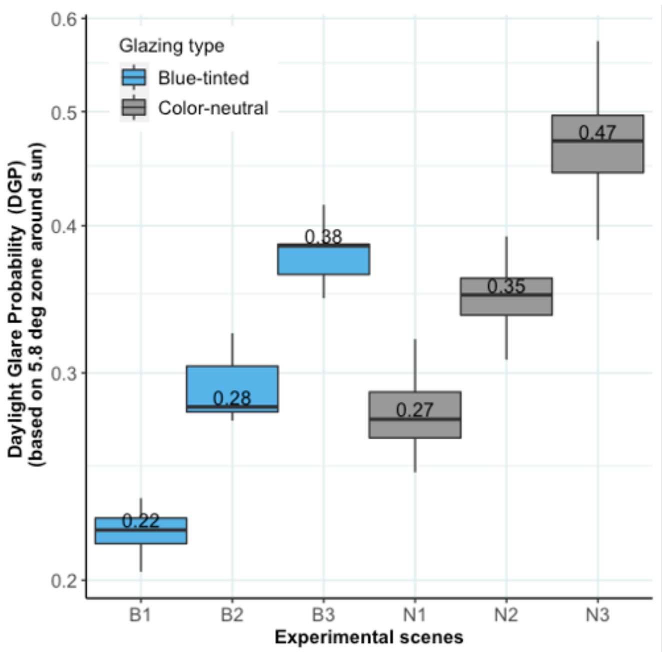

Figure 7-11 Comparison of boxplot of DGP values (calculated based on 5.8° zonal method, cf. Section 7.4.6.1) with medians between blue-tinted glazing and color-neutral glazing

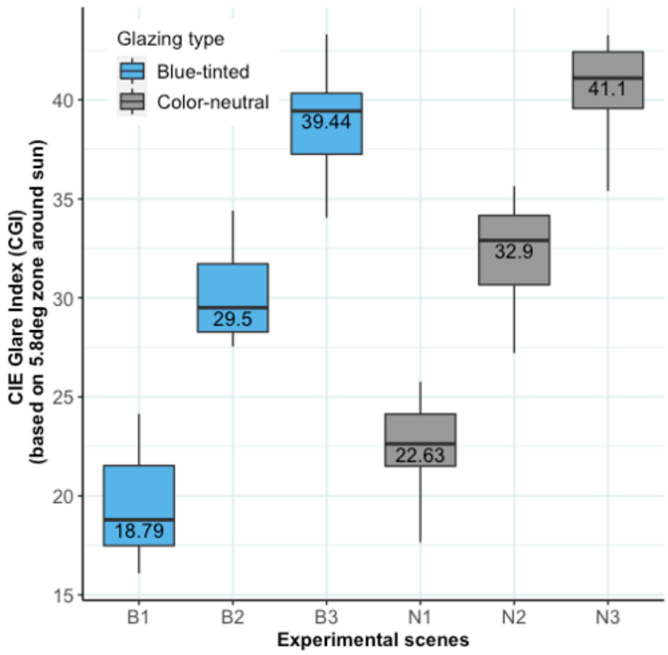

Figure 7-12 Comparison of boxplots with median values of CGI glare metrics (calculated based on 5.8°zonal method, cf. Section 7.4.6.1) between blue-tinted glazing and color-neutral glazing

7.5.2 Comparison of glare perception under blue and neutral glazing

As described in section 7.4.4, we first analysed the answers from the open-ended questions and compared them with the responses to the binary glare questions, to determine whether the participants were bothered by glare even when it wasn't asked specifically in the question. We found that amongst the participants who reported "Yes" to the binary question in color-neutral conditions, 83% of them had actually written either glare or sun or bright light as a disturbing factor in their answers to the open-ended question. Similarly, under blue-tinted glazing, 82% of the participants had mentioned sun or glare or bright light as disturbing factors, which seems, in both cases, to confirm that glare was the primary experimental variable in both the studies.

Figures 7-13 and 7-14 show the percentage of participants experiencing discomfort from glare, represented as bar plots on a binary "Yes/No" scale and on a four-point ordinal scale, respectively. The distribution of votes from both scales follows a similar trend, therefore indicating a consistency in the participants' answers and a reliability of asked questions. Overall, participants experienced discomfort more often in blue-tinted glazing (52% voted 'Yes') compared to color-neutral glazing (42% voted 'Yes') even though the calculated glare metrics were higher in color-neutral glazing conditions: based on these predictions, the probability of experiencing glare would be expected to be higher in color-neutral cases, which was not proved to be true. From Figures 7-13 and 7-14, it can, on the contrary, be inferred that participants were tolerating glare *better* in color-neutral glazing compared to blue glazing despite the conditions being a priori more prone to glare (higher glare metric values).

Comparing conditions B1 to N1 in Figure 7-13, which are the two best performing conditions in terms of controlling glare within each study, the percentage of participants experiencing discomfort are 3% lower in N1 (color-neutral glazing) compared to B1 (blue glazing), 13% versus 16% respectively, even though the mean CGI and DGP values are higher for N1 compared to B1. Similarly, comparing B2 to N2, a higher percentage (17% higher) of participants report being comfortable under N2 (64%) compared to B2 (47%), whereas glare metrics are lower for B2. Likewise, condition N3 (22%) has a 11% lower ratio of participants experiencing glare compared to B3 (11%). Figure 7-14 with the four-point response labels presents a similar distribution of votes and a higher percentage of participants reporting glare in blue-tinted glazing compared to color-neutral glazing.
In summary, we compared glare conditions shown to participants with all three types of metrics: contrast driven metrics (CGI, Figure 7-12), hybrid metrics (DGP, Figure 7-11) and solely saturation

(adaptation) based metrics (Ev, Figure 7-9). In all the cases, glare metrics always had higher values in case of color-neutral glazing indicating that both the contrast and saturation effects are higher under color-neutral scenarios. However, deriving from participants' subjective responses (Figure 7-13 and 7-14), they were better able to tolerate these higher predicted glare values in color-neutral scenarios.

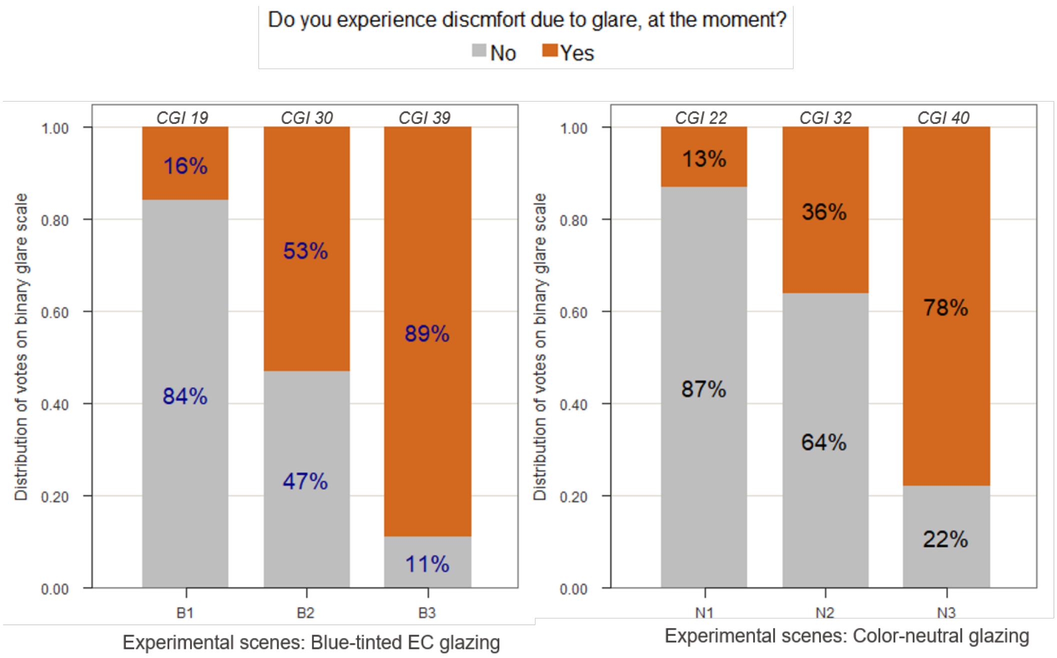

Figure 7-13 Distribution of subjective glare votes in three experimental scenes under blue-tinted EC glazing (left) and color-neutral glazing (right) on Binary response labels with mean CGI values of the experimental conditions

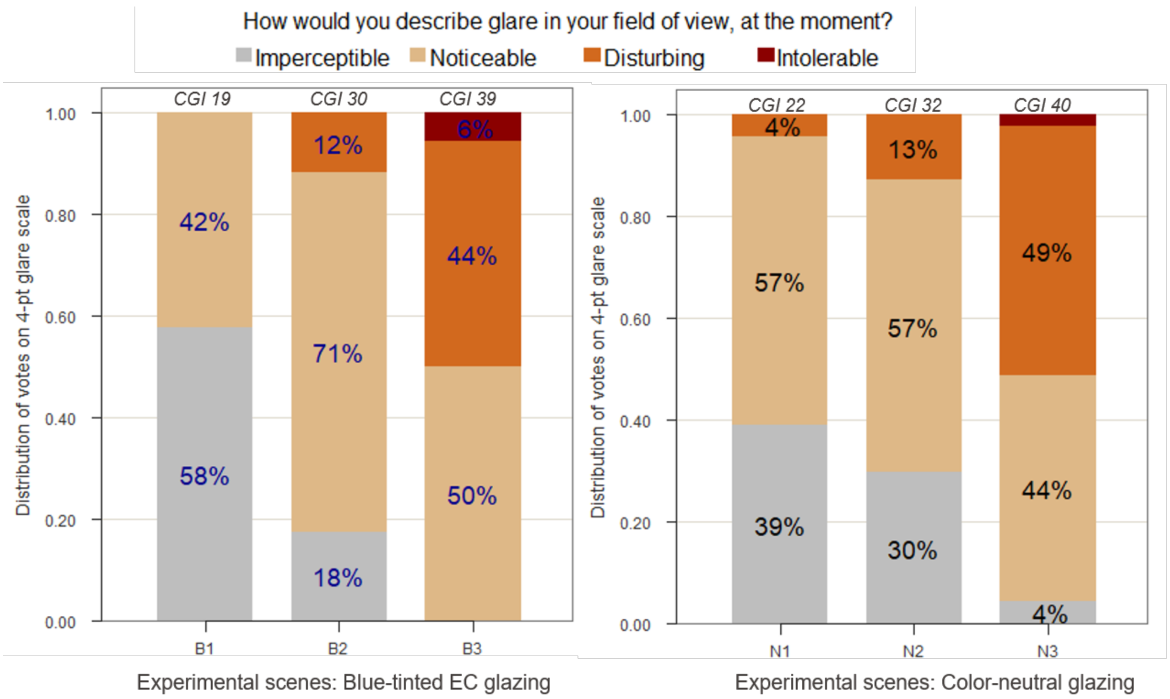

Figure 7-14 Distribution of subjective glare votes in three experimental scenes under blue-tinted EC glazing (left) and color-neutral glazing (right) on 4-point Likert response labels with mean CGI values of the experimental conditions

7.5.3 *Comparison of discomfort glare thresholds between blue and neutral glazing*

To further quantify the descriptive analysis shown in the previous section, that seems to indicate a higher glare tolerance for neutral glazing compared to blue glazing, we determined the glare metrics thresholds at which participants report discomfort under blue and color-neutral conditions. We applied ROC and PR-curve methods on the binary responses as described in section 7.4.7 to derive optimal thresholds.

First, we established the effectiveness of the chosen glare metrics (DGP and CGI) in predicting participants' perception of discomfort glare by applying a Spearman's rank correlation and an AUC analysis, as reported in Table 7-4. The Spearman's rank correlation between the glare metrics DGP and CGI and the glare responses on four-point ordinal labels were found to be between 0.67-0.63 for the blue-tinted glazing and 0.62 for the color-neutral glazing. As per Cohen's effect size thresholds (Cohen, 1992), $\rho > 0.5$ are classified as a strong effect. AUCs from the ROC analysis inform on the metrics' ability to distinguish between comfort and discomfort glare scenarios. Table 7-4 reports the AUCs for DGP and CGI for blue-tinted and color-neutral glazing between 0.80 to 0.88. As per Hosmer-Lemeshow (Bertolini et al., 2000), AUC > 0.8 are categorized as an excellent discriminator of the binary classification model. Therefore, both the performance evaluation show that the glare metrics based on contrast and hybrid effects are reliable in predicting glare.

Table 7-5 reports the optimal glare thresholds between the comfort and discomfort glare based on binary "Yes/No" questions calculated using ROC and PR-curve methods. The distribution of binary answers for blue-tinted glazing is 47%-No and 53%-Yes responses whereas for the color-neutral glazing is 56%-No and 44%-Yes responses. As shown in Table 7-5, we calculated these thresholds first on the original dataset, then on two subsamples of the original dataset for further validation. This subsampling was performed for a more careful and strict evaluation of the data. We made sure that the calculated glare thresholds were not affected by the range of conditions shown to the participants by correcting for the higher stimuli in the original color-neutral dataset that may drive higher glare thresholds. In the subsample-1, we recalculated glare thresholds over a subsample of the data with conditions B2, B3 and N1, N2. In these selected conditions, the stimuli were higher for blue-tinted glazing compared to color-neutral glazing. In the subsample-2, we extracted a random subsample (70 datapoints) of color-neutral dataset with 1000 iterations, which has a similar distribution to the blue-tinted dataset. Figure 7-15 shows the boxplot comparison of these three samples with median values and mean location.

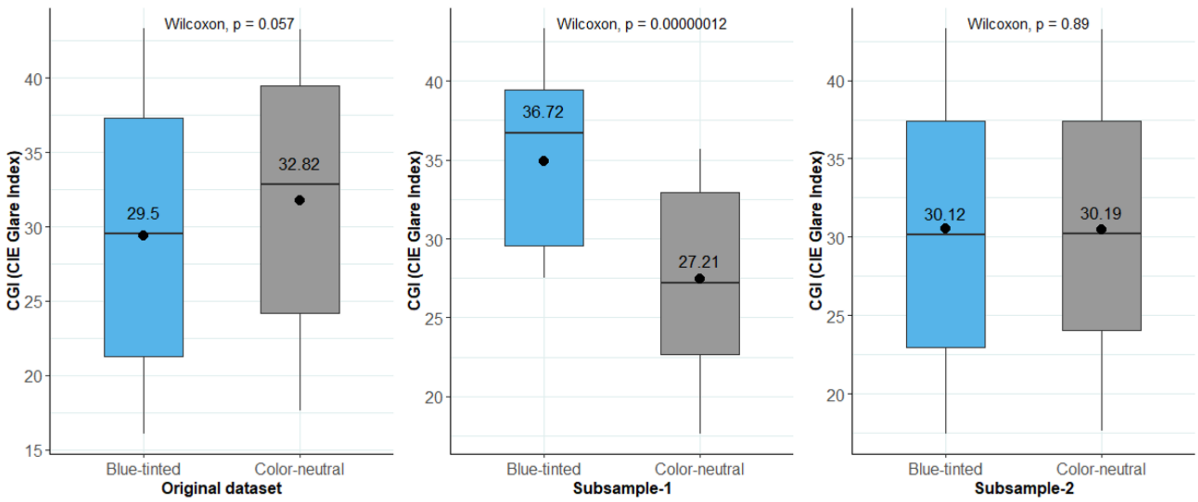

Figure 7-15 Comparison of distribution of CGI values (calculated based on 5.8° zonal method, cf. Section 7.4.6.1) between blue and color-neutral glazing in original dataset, subsample-1 and subsample-2 used for glare threshold calculations.

From Table 7-5, it is clear that glare thresholds are always higher for the color-neutral cases compared to blue-tinted cases using both ROC and PR-curve methods for the original dataset and for the two subsamples as well. These findings hold true for all the chosen glare metrics, indicating higher tolerance of glare in color-neutral and therefore confirming a strong influence of the glazing spectrum on glare perception.

Table 7-4 Spearman rank correlation coefficients between glare metrics and glare responses on four-point ordinal labels

Indicator	**Glazing**	**DGP**	**CGI**
Spearman's rank correlation coefficient (ρ)	Blue-tinted	0.67	0.63
	Color-neutral	0.62	0.62
AUC	Blue-tinted	0.87	0.88
	Color-neutral	0.88	0.86

Table 7-5 Optimal glare thresholds for daylight glare metrics (calculated based on 5.8° zonal method, cf. Section 7.4.6.1) under blue-tinted and color-neutral glazing obtained using ROC and PR-curves methods on three datasets

Dataset	**Metric**	**ROC thresholds**		**PR-curve thresholds**	
		Blue-tinted	**Color-neutral**	**Blue-tinted**	**Color-neutral**
Original	CGI	31.7	37.1	29.5	39.2
	DGP	0.29	0.37	0.28	0.44
Subsample-1	CGI	31.2	33.4	27.8	29.1
	DGP	0.29	0.32	0.27	0.44
Subsample-2	CGI	31.6	37.5	29.5	39.4
	DGP	0.29	0.33	0.28	0.44

7.5.4 Comparing modified glare metrics between blue and neutral glazing

In this section, we compare the modified glare metrics calculated as per the method described in section 7.4.6.2. Our hypothesis is that the modified glare metrics values should be higher for the blue-tinted glazing compared to the color-neutral glazing for the experimental conditions where the discomfort responses were also higher for the blue-tinted glazing. In other words, to be able to explain the effect of spectrum revealed in this study, the spectral discomfort glare sensitivity functions should result in higher glare metrics values for blue-tinted glazing between scenes B1 and N1, B2 and N2, and B3 and N3. We modified the CGI and DGP metrics as per eq. 6 and 7 based on the four spectral discomfort glare sensitivity functions listed in Eq. 1 to 4. For the sake of brevity, in this section we only present modified-CGI metric comparison between the scenes B2 and N2, as shown in Figure 7-12. Remaining scenes which are not presented here follow a similar trend.

Comparing the standard CGI metric weighted by CIE $V_{2°}(\lambda)$ with the ones weighted by CIE $V_{10°}(\lambda)$, $V_{DG1}(\lambda)$, $V_{DG2}(\lambda)$ and $V_{DG3}(\lambda)$, the mean CGI difference between blue and neutral cases tends to decrease most in cases where the $V_{DG1}(\lambda)$ function is used, as it includes a substantial contribution from S-cone fundamentals (cf. Equation 1). This is coherent with blue glazing transmitting more in the S-cone sensitive region and hence the increase in CGI value is higher for blue glazing compared to neutral glazing. For the $V_{DG2}(\lambda)$ and $V_{DG3}(\lambda)$, the difference between the blue and neutral datasets increases further due to the higher weighting of the L and M cones (cf. Eq. 2 and 3). Nevertheless, all the implemented functions are unable to provide higher CGI values for B2 experimental condition compared to N2 condition where the participants experienced stronger glare sensation. Since these functions were developed based on the experiments done under monochromatic electric light sources, there application under broad spectrum daylight glare sources seems to be limited.

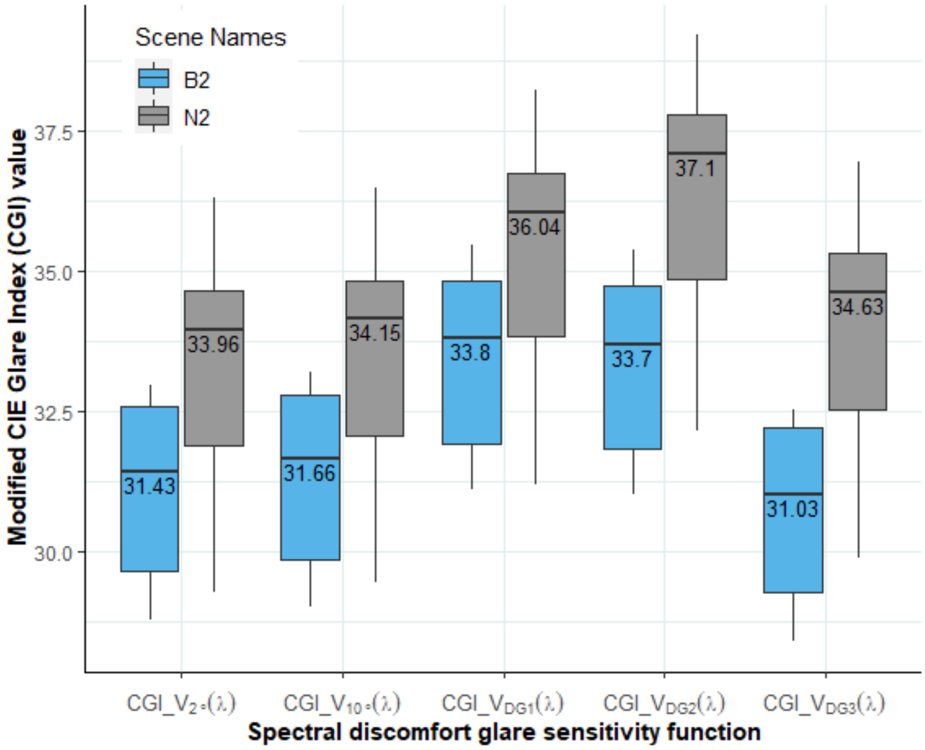

Figure 7-16 Comparison of adjusted DGP values as per different spectral weighting functions for discomfort glare

7.6 Discussions

The focus of this study was to determine the difference in glare perception when comparing a glare source (namely the sun disc) visible through blue-tinted versus color-neutral glazing. The focus is therefore not to validate the performance of glare metrics in predicting glare in such scenarios, nor to derive glare thresholds for practical applications. We should thus note that the glare metrics thresholds reported in this study are not be directly compared in absolute terms to the previous studies (Jain, Karmann, et al., 2022; Wienold et al., 2019a) or to the ones reported in building standards such as EN17037 (CEN, 2019), due to the zonal calculation method used in this study unlike other studies. The same applies for the implementing sun window transmittances in controlling glare for façade design applications: the threshold transmittances to control glare can vary when there is similar level of adaptation between blue and color-neutral glazing unlike in this study. However, in order to have a sense of glare conditions to which participants were exposed to and compare them between the two glazing types, it was necessary to first evaluate whether the glare metrics were applicable to such scenarios (i.e. can be expected to reliably predict glare).

One limitation of this study comes from the difference in stimuli between the blue-tinted and the color-neutral glazing conditions owing to the differences in their glazing transmittances. Due to this, the adaptation levels are higher in color-neutral glazing. Since DGP could overestimate the adaptation effect as discussed in previous studies (Hirning et al., 2017) (McNeil & Burrell, 2016; Quek et al., 2021), CGI is relied upon to compare the glare metrics between the two studies. We account for the stimuli differences by performing an additional analysis on a subsample of similar stimuli distribution (cf. section 7.5.3). Another limitation of this study is that due to the lack of measurement instruments to measure sun spectra and the limited availability of spectral measurements, we had to implement a calculation method that uses standard sun spectra, which could differ from actual onsite sun spectra due to the atmospheric conditions and this can create discrepancies to some extent in the calculated glare metric values using this method. However, since we performed a relative comparison between the modified glare metrics, these discrepancies can be ignored. We also made sure to conduct the measurements only during stable weather conditions with clear sky. We also acknowledge that we have slightly higher position indices in color-neutral glazing compared to blue glazing (Figure 7-7), that can therefore create lower glare levels. To overcome this, we conducted an additional evaluation on a subsample of color-neutral glazing which has similar distribution of position indices in comparison to blue glazing, we again found higher glare thresholds (neutral-CGI= 36.5, blue-CGI=31) for color-neutral conditions. It should also be noted that the results found in this study are only valid for the lighting intensity and spectrum being tested. These aspects will change depending on many factors including glazing properties, glazing configuration, possible use of electric light in combination of daylight, climate, and location. The measurements and surveys based on new field studies with EC glazing should thus be evaluated to further conform on the current findings. Additionally, future studies can implement and test the upcoming technology of neutral-tinted EC glass to create the color-neutral scenarios.

Due to the exposure to relatively higher sun luminance values under color-neutral glazing, we made sure that participants' vision was not impaired under the glare from the sun. This was confirmed by implementing a Landlot C contrast test (Bach, 1996a). Participants did the contrast test under constant electric light setting without any daylight in the introduction phase as a baseline measure; afterwards, they repeated the same test (with randomized characters) under each daylit experimental condition. We compared the results of the baseline test with the test conducted under daylight and did not find any significant differences between them. Therefore, these conditions conform to the discomfort glare definition given by CIE where vision is not impaired.

While we found a strong influence of color on discomfort glare perception from daylight, none of the implemented spectral discomfort glare sensitivity functions could explain this influence. Based on literature, we have formed some hypotheses to explain this influence which should be further investigated. The first hypothesis relates to the Helmholtz-Kohlrausch effect (H-K effect) which indicates that more saturated chromatic stimuli appear brighter than the less saturated chromatic or achromatic stimuli of same luminance (Judd, 1958). Although this effect is only shown in the context of brightness perception, study by Yang et. al (Yang et al., 2018) have shown that glare perception is strongly correlated with brightness perception. In the present study, the saturation component of the sun seen through the blue-EC glazing was 65%, whereas, for the color-neutral glazing, it was 0%. Therefore, as per the H-K effect, it can result into the sun appearing brighter under more saturated blue glazing compared to less saturated color-neutral glazing. It can thus be hypothesized that, similarly to brightness, glare perception is mediated by both achromatic (or luminance) and chromatic channel, unlike luminance. To examine this hypothesis, color brightness models can be applied to predict glare perception from self-luminous colored stimuli. Another hypotheses is based on the literature on non-visual effects of light which have shown the role of melanopsin in regulating the pupillary light reflex and greater steady-state pupillary constriction under blue-light exposure (McDougal & Gamlin, 2010; Spitschan, 2019). This could be a potential reason why occupants perceived blue daylit scenes more discomforting than color-neutral daylit scenes in our study. Furthermore, a recent study have suggested that the melanopsin signals play a crucial role in the estimation of perceived brightness (Yamakawa et al., 2019); therefore, in addition to cones, melanopsin should be considered as possibly contributing to glare prediction, which would have a higher impact in the presence of light in the short-wavelength ranges.

7.7 Conclusion

In this study, we compared perceived discomfort glare under blue-tinted versus color-neutral glazing of different (low) transmittances, with the aim to determine the effect of spectrum. By performing a between-subject evaluation, we found that the study participants were better able to tolerate glare under color-neutral glazing, whereas they perceived it more strongly under blue glazing. Participants experienced similar or lower levels of discomfort glare under color-neutral glazing which had higher values of predicted glare metrics than the blue-tinted glazing.

Our findings show that the spectrum of a glare source strongly influences people's glare perception under daylit conditions. This relationship is of complex nature and remains unexplained by the previously reported spectral sensitivity functions for glare. Currently, the effect of spectrum is not accounted for in any of the glare metrics and there are also no studies evaluating the effect on glare perception at different wavelengths under broad spectrum conditions. There is therefore a need to redefine the luminance and illuminance terms in glare models to incorporate the effect of spectrum. Colored glazings of significantly different spectra are expected to create different levels of glare perception, which needs to be further evaluated by future research to better understand the relation between spectrum of glare source and glare perception. Future works should be focused on quantifying this effect of spectrum and incorporating it in modified glare models. For the field and laboratory glare studies conducted under colored daylighting or electric lighting conditions, more emphasis should be given on spectral measurements rather than just the luminance and illuminance measurements.

While this study was focused on the short wavelength shifted broad spectrum, more studies should be conducted to determine the glare perception along the entire visible spectrum, which will provide better insights and enhance our understanding of the spectral sensitivity of human eye under brightly lit glary conditions with chromatic glare sources.

Acknowledgement
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Key outcomes of this study are:

- Participants were better able to tolerate glare in under color-neutral conditions compared to the blue-colored conditions with sun disc in field of view.
- None of the previously proposed spectral glare sensitivity functions were able to anticipate the differences in glare perception between neutral and blue conditions.

The learnings from this study, that relates to the subsequent chapter on the influence of color on discomfort glare are:

- Spectral discomfort glare models proposed under colored electric lighting have limited applicability in colored daylight (filtered by colored glazing) condition.
- Based on the findings, colored glazings of significantly different spectra can be hypothesized to create different levels of glare perception which will be investigated in the subsequent study.

Chapter 8

Influence of color of daylight filtered by colored glazing on discomfort glare

Objectives

The objectives of the study presented in this chapter are:

1. To determine the influence of color of sun disc, altered by using colored glazing of colors red, green, blue or neutral, on discomfort glare perception.

2. To determine whether the effect of color, if any, would sustain at two different glazing transmittance levels.

Influence of color of daylight filtered by colored glazing on discomfort glare

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Abstract

The influence of color on discomfort glare induced by daylight has not yet been investigated, despite the known effect of color in electric lighting when it comes to visual comfort. We conducted a controlled laboratory study to fill this gap, whereby we examined the influence of daylight filtered by colored glazings – with the sun disc apparent in the field of view as the main glare source – on discomfort glare perception. 56 participants were exposed to four daylight conditions in an office-like setting, which differed only in glazing color (red, blue, green, and neutral). Two levels of glazing transmittances (τ_v ~0.37% vs. ~2.5%) were tested, which led to 28 participants experiencing each transmittance level for all four glazing colors. Results revealed a strong impact of color on the participants' glare perception, with more participants reporting glare in the red and blue conditions compared to the neutral and green conditions. The red condition was found to be the most disturbing, closely followed by the blue one, while the green condition was the least disturbing (though very close to the neutral one). These findings suggest that applying the V(λ) function for the calculation of the glare source luminance in existing glare metrics as spectral weighting is not effective enough.

8.1 Introduction and background

Windows in a building play a significant role in its occupants' well-being, in the building's cost and architectural expression (Leather et al., 1998b; Turan et al., 2019). Adequate access to daylight and views to the outdoors have been shown to enhance comfort, cognitive awareness, stress reduction, mood, sleep patterns, and overall health (P. Boyce, 2022; Farley Veitch et al., 2001; Heschong et al., 2002; Jamrozik et al., 2019). However, excessive or inappropriate daylight can also result in visual discomfort caused by glare, which is especially prevalent in highly glazed commercial buildings. The visible light transmittance and glazing color of windows are key factors that impact the daylight quality and quantity and therefore also impact visual comfort in buildings. Smart glazing, such as Electrochromic (EC) glazing, allows for modulation of transmittance to mitigate glare risks (EU Commission, 2003) but at the same time they can also significantly change their color(Baetens et al., 2010). Recent research has assessed the impact of EC glazing transmittance on discomfort glare perception and established annual transmittance thresholds (Jain, Karmann, et al., 2022; Wienold et al., 2022). However, although a few studies have investigated the effect of colored façade on visual quality, preference, and/or acceptance, the impact of glazing color on discomfort glare has not yet been properly evaluated.

Such studies include the one by Liang et. al (Liang et al., 2018, 2021) on colored artificial windows, which found that bronze glazing had higher acceptance than blue glazing, even though the visual performance was lower in bronze glazing compared to blue glazing. Similar results were found in another study relying on a scale model (Arsenault et al., 2012), where daylight filtered through bronze glazing was preferred over blue and neutral glazing. A different study conducted in Beijing with 11 subjects reported that clear and bronze glazing were rated more visually comfortable than green, dark blue, and red glazing (X. Chen et al., 2019). A study by Chinazzo et al. (Chinazzo et al., 2018) found that participants were more visually comfortable under color-neutral glazing compared to blue and orange-colored glazing. Overall, warmer-colored daylit environments were quite consistently found to be more visually acceptable, in these various studies, than cooler-colored environments, which, by extension, can provide some prospective insights on discomfort glare perception.

In parallel, the relation between discomfort glare and color of electric light, more specifically the Spectral Power Distribution (SPD) of LED headlamps, has been studied in recent years. Earlier studies by Flannagan et. al (Flannagan, 1999b; Flannagan et al., 1989a) conducted with monochromatic lights of blue, green, and red colors at six different peak wavelengths have shown that the participants experienced the highest discomfort under blue lamps followed by red and green lamps. The authors also concluded that the CIE spectral sensitivity function V(λ) ((CIE 086-1990, 1988)) was not suitable for characterizing discomfort glare. Subsequent studies on colored LEDs, High-Intensity Discharge lamps, and tungsten halogen lamps reported similar results of perceiving higher discomfort glare under shorter wavelengths, while no significant difference was observed in glare between all other peak wavelengths of red, green, yellow and white colored light sources (Bullough, 2009; Bullough et al., 2004; Fekete et al., 2010; Kimura-Minoda & Ayama, 2011; Niedling & Völker, 2018; Sivak et al., 2005; Sweater-Hickcox et al., 2013; Yang et al., 2016). Based on these findings, some studies have also proposed discomfort glare spectral sensitivity functions that were aimed at replacing the CIE V(λ)(Bullough, 2009; Fekete et al., 2010; Kimura-Minoda & Ayama, 2011; Yang et al., 2016). These proposed functions, although different from each other, all have a higher weighting in the short wavelength region compared to V(λ), while the mid- and long- wavelengths have similar weighting as V(λ) (Yang et al., 2016). In addition to SPD, several studies have also evaluated the impact of a light source's CCT (Correlated Color Temperature) on glare perception and again found that the light sources with higher CCTs (blue appearance) caused higher discomfort glare than those with lower CCTs (P.-L. Chen et al., 2015; Wei et al., 2014; Zhang et al., 2013).

All the studies with electric lighting have consistently demonstrated an effect of glare source spectra on glare perception and have repeatedly found that people perceived glare more strongly under blue-colored LEDs compared to all other colored LEDs. Recently, a similar trend was found in a user study conducted with daylight, comparing glare perception under blue EC glazing and color-neutral glazing

(Jain et al., 2023; Jain, Karmann, et al., 2022): the study showed that the participants experienced discomfort glare more strongly in blue EC glazing compared to the color-neutral glazing. This effect, revealed under daylight, could however not be anticipated by applying any of the discomfort glare spectral sensitivity functions proposed by previous studies done with electric light (Jain et al., 2023). This finding, therefore, suggests that glare under daylight might be perceived very differently compared to electric light, which should be further investigated for other colored glazings.

Given the increasing use of colored Building Integrated Photovoltaics (BIPV) glass in building façades, determining discomfort glare risks under colored facades is of practical significance. The growing popularity of BIPV façades, driven by the increasing demand for nearly Zero Energy Buildings (nZEBs), has led to an estimated annual growth rate of 40% (*Coloured BIPV*, 2019). Research suggests that colored photovoltaic glass is better suited to increase the adoption of BIPV in glass façades due to its added architectural value (Hirschl, 2005; Polo López et al., 2021; Woo et al., 2022). The use of new generation photovoltaics, such as organic photovoltaics (OPV), dye-sensitized solar cells (DSSC), luminescent solar concentrators, and perovskites, with their wide range of colors and transparency, has the potential to further increase their application in both new and retrofitted buildings (Cannavale et al., 2017; Gratzel & O'Regan, 1991). However, the spectral shifts in daylight caused by differently colored BIPV façades can have different impacts on the visual quality and comfort of indoor spaces. Furthermore, colored glass that is highly efficient in terms of power generation, such as blue, can be less efficient in terms of visual comfort requirements as evidenced in past studies (*Coloured BIPV*, 2019; Jain, Karmann, et al., 2021). Therefore, it is necessary to know how the spectral shifts in daylight caused by colored glass façades may impact discomfort glare perception.

To answer this question, we present a user study, conducted in a daylit office-like test room with colored glazing, to determine the influence of color of the sun disc on discomfort glare perception. Study participants were exposed to four daylight conditions having red, blue, green or neutral-colored glazing as a filter to the sun disc and were asked to report their glare perception under each condition. To the best of our knowledge, this is the only study that investigates the influence of spectral shifts in the light received directly from the sun disc on discomfort glare.

8.2 Objectives

The objectives of this study are:

1) To determine the influence of the color of the sun disc (altered by the colored glazing) on subjective glare perception.
2) To determine whether the effect of color, if any, would sustain at two different glazing transmittance levels.

The method and results of the study are detailed in the subsequent sections.

8.3 Method

This study follows a single-blind psychophysical procedure where we examine the relationship between glare from colored daylight (a physical stimulus) and participants' glare perception (psychophysiological response).

8.3.1 Study Design

We designed a 2x4 full factorial experiment to determine the influence of colored daylight of similar intensity on participants' glare perception. A total of eight combinations of experimental scenes were achieved with two levels of glazing transmittances (~0.37% and ~2.5%) and four levels of glazing colors (neutral glazing in addition to blue, green and red, respectively caused by colored glazing of short-, mid- and long-wavelengths dominated spectral transmittances). The color of glazing was varied within subjects while the visible light transmittance of the glazing was varied between subjects, resulting in a mixed factorial design. This design made it possible to study the influence of colored daylight while keeping the daylight intensity (glare source luminance, background luminance, and vertical illuminance at the eye) similar for a participant. Additionally, a mixed factorial design was selected as it requires fewer participants and offers greater statistical power (Charness et al., 2012). As a result, any participant was exposed to four colors of filtered daylight (whose order was counterbalanced across the participants) and only one level of glazing transmittance.

The sample size was derived based on an a priori power analysis in the G*Power 3.9.1.7 tool (Faul et al., 2009) with two groups and 4 repeated measurements, assuming an effect size of 0.30, an alpha value of 0.05 and a power of 0.95. This resulted in a required sample of 50 participants. Considering the possibility of human errors and other technical errors, we recruited a total of 56 participants. Following the mixed factorial design, two groups of 28 participants were exposed to one of the two transmittance levels and the four glazing colors.

8.3.2 Participants

A total of 56 young healthy individuals (39 male, 17 female) aged between 18 years to 30 years (mean age=22.6 years) participated in our experiments. The requirements for selection were to be in healthy conditions, not diabetic, have normal color vision (tested using Ishihara and D-15 disc arrangement test (Farnsworth, 1947; Ishihara, 1917)), no other visual impairment, have a BMI within the normal ranges, have a non-extreme chronotype (chronotype assessed using Morning-Evening Questionnaires (Horne & Östberg, 1976)), have an English proficiency level C1 or higher, not to use drugs and not depend on alcohol, to be aged between 18 to 35 years. To avoid response bias, other inclusion criteria were: to not recruit from the disciplines related to the investigated field (i.e., architecture and civil engineering), and to not have any link to the researchers' topic or the laboratory. The project protocol was approved by the Cantonal Ethics Commission '*Commission Cantonale d'éthique de la recherche sur l'être humain'* (Lausanne, Switzerland, ref. No. CER-VD 2020-00667). Participants provided their written informed consent before the experiments and were compensated as per the local regulations.

8.3.3 Test facility and measurements

The study was conducted in an office-like test chamber (Figure 8-1a) on the EPFL campus in Lausanne, Switzerland (46°31'00.4" N, 6°33'47.1" E). The test chamber is 6.55 m deep, 3.05 m wide and 2.65 m high with glazed south and north facades (Window-to-Wall-Ratio 62%). Tests were conducted on sunny days with clear skies and stable weather conditions. Daylight was the only source of light during the experiments entering through the south façade while the north façade was completely blocked by a white curtain. Electric light was used only for the introduction phase of the experiment (further detailed in section 8.3.5). Due to the site location and climate, experiments could only be conducted during sunny days between October and March (2021-2022) from 09h00 to 15h00 to get sun exposure and benefit from the low sun angles.

Figure 8-1 shows the test room layout together with images taken from inside and outside the room. Participants were given a work desk with a computer screen (Figure 8-1b) facing the south façade. Participants' desk was rotated as per the sun position to always have the sun visible in their central Field Of View (FOV) as a glare source during the exposure. Another desk with a computer at the back of the room was used by the researcher facilitating the experiments. The test room was equipped with additional instruments to measure the indoor thermal and visual parameters. Figure 8-1c provides the test room layout with the location of the equipment used for measuring the daylight's spectral properties, horizontal and vertical illuminance, the luminance distribution within the participant's field of view, and the room temperature.

An indoor climate meter (Testo 480), placed near the participant's desk (Figure 8-1c), was used to continuously measure and monitor air temperature, relative humidity, airflow, and CO_2 content of the test room. The temperature was kept within a comfortable range (21 ± 2°C) by using a room heater. The participant's desk was equipped with four illuminance sensors (Hagner Special Detector SD2) to continuously measure the light levels. Two of these sensors were installed on the left and the right of the participant's desk to measure horizontal illuminance. The remaining two sensors were installed at the front and the back of participant's computer screen to measure vertical illuminance. We used an absolute-calibrated luminance camera (LMK 98-4 color HighRes by Technoteam (Gmbh, n.d.) equipped with X, Y (V(λ)) and Z filters) to capture luminance and High Dynamic Range (HDR) color images at the participant's eye level before and after each experiment condition. The camera has a fisheye lens (Dörr Digital Professional DHG, equidistant projection) with a FOV of 160° post-calibration and two Neutral Density (ND) filters ND1.8 (combined factor 3134.8) to capture the sun without any pixel overflow. We also mounted, at the participants' eye level, a hand-held illuminance sensor (LMT) to measure the vertical illuminance and a spectrometer (Jaz OceanOptics) with a cosine corrector below the camera lens to measure spectral irradiance. All measurements at the participants' eye level were done twice for each daylight exposure: at the beginning and at the end of the exposure.

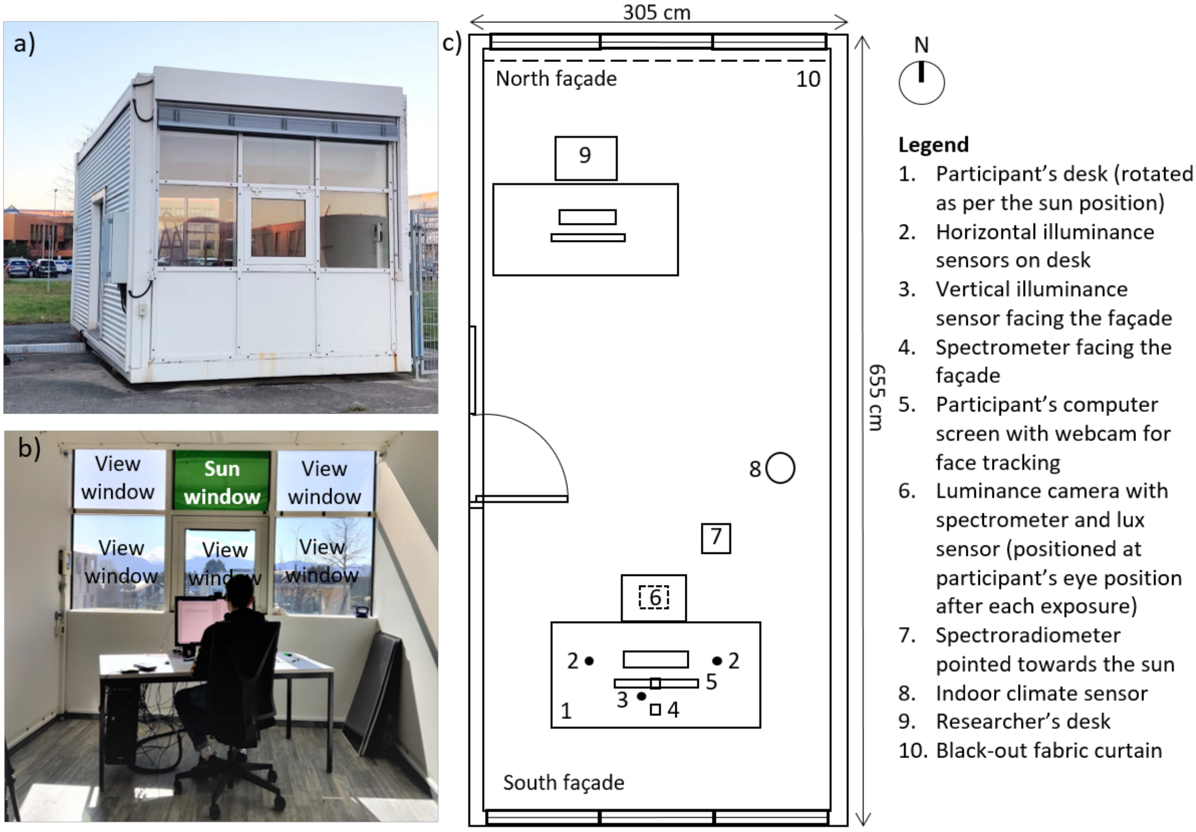

Figure 8-1 a) South façade of test room from outside, b) Test room from inside with the participant taking part in the experiment, c) Test room layout with location and description of the equipment.

In addition, a Spectroradiometer (CS-1000A by Konica Minolta) was used to measure the SPD of the sun visible behind the colored glazing at the participant's eye level. The CS-1000A is equipped with an ND3 filter (factor 755.7) and a standard SLR (single lens reflex) optical system that allows precise targeting with a measuring angle of 1°. The viewfinder attached to the spectroradiometer was used to point the sensor at the sun to measure the SPD. All the ND filters (Type: B+W) used in the experiment exhibit a nearly constant spectral transmission which was essential to capture the colored sun without any error. Since many other ND filters have high transmittance in long-wavelength regions, therefore, all the filters were measured to ensure constant spectral transmission. We also measured global (total) and diffuse solar irradiance (W/m2) with a Pyranometer installed near the test room location (SPN1, wavelength range: 400nm-2700nm) to monitor the weather conditions. All the continuous measurements were done at a 30sec interval.

In parallel to environmental measurements, we also recorded participants' pupil size using eye tracking glasses, Pupil Core (Kassner et al., 2014), that participants wore during the exposure to experiment conditions. Additionally, a webcam was used to record their faces during the exposure to extract their gaze behavior and head movement from the recordings using a deep learning-based tool called Openface (Baltrusaitis et al., 2018). However, these measurements are not evaluated and are out of the scope of the current paper.

8.3.4 Experimental conditions

Each participant was exposed in randomized order to four experimental conditions that were created by varying the color (either blue, green, red or neutral) of one of the three upper windowpanes facing the sun (labeled ‘sun window’ in Figure 8-1b) as shown in Figures 8-1 and 8-2. The location of the colored upper windowpane was changed during the experiment depending on the sun's position. We only changed the color of the sun window and not the color of the whole glazed façade, because our goal was to maintain the indoor colors as natural as possible, thereby avoiding any unwanted bias due to distorted color perception of indoor elements. The window transmittance of the colored ‘sun window’ was kept similar (either low or high) across the four scenes shown to each participant. Two levels of window transmittance (each applied to all four colored conditions) resulted in a total of eight experimental conditions (figure 8-4) that we labeled: blue_low, green_low, red_low, and neutral_low for the colored glazings with low transmittance and blue_high, green_high, red_high, and neutral_high for the colored glazings with a higher transmittance (still low in absolute terms). The remaining windowpanes (labeled ‘View windows’ in Figure 8-1b) were kept at the same visible transmittances (τ_v =8.28%) for all the experimental conditions: this transmittance was chosen to allow reaching the recommended daylight level on the work desk (at least 300lux(CEN, 2019)) while avoiding glare from the view, window since our goal was to have the sun visible through the colored glazing as the only glare source. Table 8-1 describes the properties of all the glazings used in the experiments.

8.3.4.1 Glazing selection criteria and properties

To achieve the objectives as mentioned in section 8.2, we selected the glazing transmittance and color with pre-defined criteria which are described below. A series of pre-test measurements with HDR imaging was conducted to reach the final eight experimental conditions fulfilling our criteria.

The criteria for selecting the three saturated colored glazings (blue, green, and red colors) were to have a minimum overlap between their respective peaks in spectral transmittance, covering distinct parts of the visible spectrum: their resulting SPD characteristics are shown in Figure 8-3. The color-neutral glazing was chosen as a reference scenario to compare against the three colors since it is the most widely used glazing. As the goal of the experiment was to keep a similar sun luminance across all colored conditions, we tried our best to get colored glazing of the same visible transmittance. After several iterations of ordering and measuring many colored films from different manufacturers, we were able to approximately match the visible light transmittances (weighted over $V(\lambda)$) of four colored films in two groups of low and high transmittance within acceptable differences (maximum relative difference between the transmittance is 11%) and with the desired spectral transmittances (Table 8-1 and Figure 8-3).

The criteria for selecting two glazing transmittance levels (high and low) were to evaluate whether the effect of color could be observed at different glare source luminance levels. The two transmittance levels adopted for the glazings were, on average, 2.5% for the high-level glazings and 0.37% for the low-level ones (cf. Table 8-1). These values were selected in order to create two non-overlapping levels of sun luminance where a range of glare responses could be expected even considering the rather high inter-individual variability in glare sensitivity. These values were also checked to fall within a similar range as a past study with neutral glazing where glare perception was evaluated at low levels of transmittances (Jain et al., 2023).

Figure 8-2 Example images of four experimental scenes shown to each participant with glazing colors blue, green, red and neutral from left to right

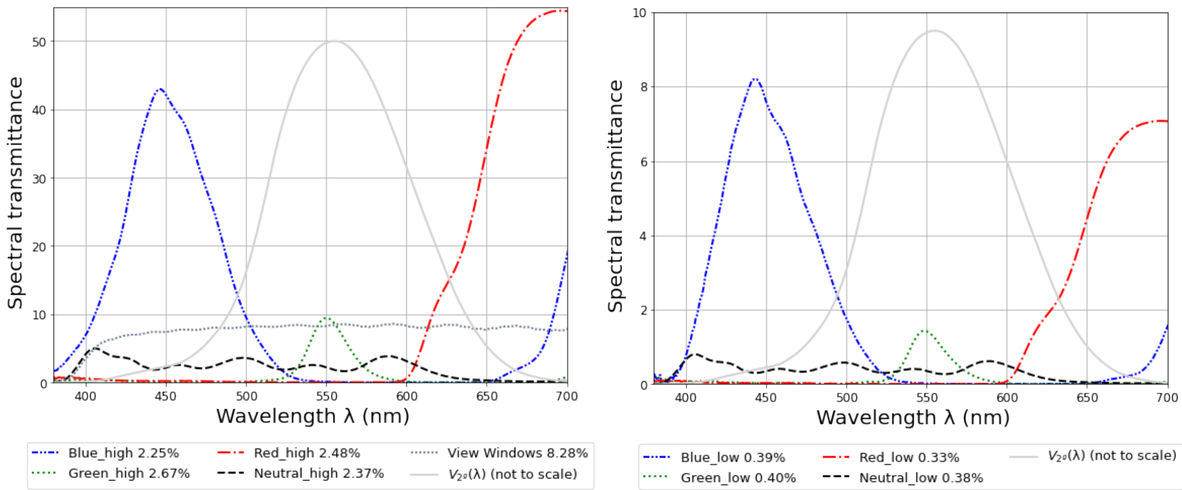

Figure 8-3 Measured spectral transmittances of colored glazing with high transmittance levels (left) and low transmittance levels (right) in comparison with the CIE 1988 $V_{2°}(\lambda)$

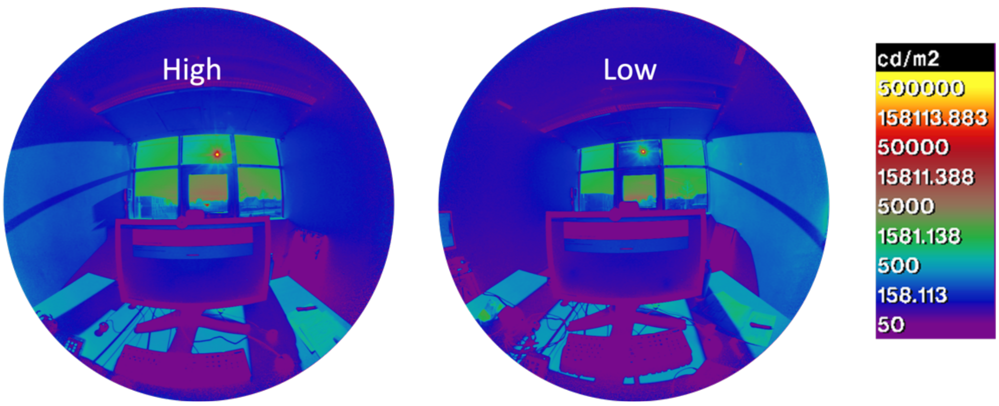

Figure 8-4 Example of Falsecolor fisheye luminance maps of the high and low intensity conditions experienced by the participants

Figure 8-4 shows the falsecolor luminance images of the two example scenes of high and low conditions that were experienced by the participants (pictures taken at eye level). To create the colored sun window, we applied colored films between two transparent acrylic panels (τ_v =95%) and manually attached the panels to the existing fixed window glazing (τ_v =79%) facing the sun. We measured the spectral transmittance of each glazing unit (combination of colored filter and fixed window) and their angular behavior in a laboratory setup described by Steiner et. al (R. Steiner et al., 2005). The measurement uncertainty of normal-hemispherical transmittance ($\tau_{v,n\text{-}h}$) is estimated to be less than

0.001. Spectral transmittances are plotted in figure 8-3 for the eight colored glazings and the view glazing in reference to CIE 1988 $V_{2°}(\lambda)$.

Table 8-1 demonstrates the measured $\tau_{v,n-h}$ of the glazing along with their chromaticity coordinates. The chromaticity coordinates are calculated based on based on CAM02-UCS color space (Color Appearance Model 02- Uniform Color Coordinates) due to its higher performance accuracy compared to other color models (Luo et al., 2006). The CAM02-UCS color space is based on CIE CAM02 (CIE, 2004) model and has coordinates J' (lightness), a' (red-green), b' (yellow-blue), where (a', b') characterizes the hue-chroma plane. We converted the CIE XYZ coordinates to CAM02-UCS space by following the conversion method described in TM-30-20 (David et al., 2015).

Table 8-1 Properties of window glazing used in the experiment.

Glazing	Visible light Transmittance ($\tau_{v,n-h}$) weighted by V(λ)	CIE 1976 UCS chromaticity coordinates		CAM02-UCS Chromaticity		
		u'	v'	J'	a'	b'
Blue_low	0.39%	0.17	0.15	202.1	-38.0	-90.0
Green_low	0.40%	0.13	0.57	206.3	-54.7	66.9
Red_low	0.33%	0.55	0.51	206.3	94.6	44.0
Neutral_low	0.38%	0.19	0.48	206.0	-14.0	12.0
Blue_high	2.25%	0.17	0.16	223.5	-53.3	-96.3
Green_ high	2.67%	0.13	0.57	226.4	-62.9	82.4
Red_ high	2.48%	0.55	0.51	227.5	106.0	53.9
Neutral_ high	2.37%	0.19	0.48	226.0	-18.4	15.8
View windows	8.28%	0.20	0.49	232.7	2.6	32.9

8.3.5 Experimental procedure

Each experimental session lasted about two hours with one participant at a time and maximum of two participants in a day. The 2-hour long procedure is visualized in figure 8-5. The first part (named "Introduction" in figure 8-5) was conducted under electric light with closed window blinds, during which participants were introduced to the test procedure following a single-blind approach to avoid response bias (Nichols & Maner, 2008). Afterward, they did a D-15 disc arrangement color blindness test and then answered a background survey. This was followed by a short (~10mins), non-invasive measurement of the participant's *MPOD* (Macular pigment Optical Density) for both eyes as a part of another project related to the influence of MPOD on glare sensitivity (Jain et al., (under preparation)).

After the introduction step, participants were exposed to four colored daylit scenes, with dark-adapted breaks in between. Each scene started with a typing task (~10mins), followed by answering survey questions (~8mins), and ended with a break (~5min). During the break, participants were given an eye mask to cover their eyes and headphones to listen to music while the researcher prepared the test room for the next scene by opening the window blinds, changing the color of the sun window, and rotating the participant's desk to face the colored gazing and see the sun in their FOV. During that same break, the researcher also captured an HDR image, measured the vertical illuminance, the spectral irradiance at the participant's eye level, and the spectral irradiance of the sun visible behind the colored glazing. After the break, the participants were asked to type a predefined text shown on the screen for 10min to simulate an office environment. More importantly, this task allowed them to visually adapt to the lighting condition. The text to be typed varied between visual scenes and all texts had been evaluated beforehand as having the same level of readability (checked with (*Text Analysis Tool*, 2020)).

Afterward, the participants answered a comfort survey reporting their thermal, visual, and color perception. This part took from 6mins to 10mins (average~8mins) depending on each participant's speed. This sequence was repeated for the four scenes. The whole experiment ended with a debriefing survey where the participants provided their overall feedback on the comfort they perceived in all four conditions.

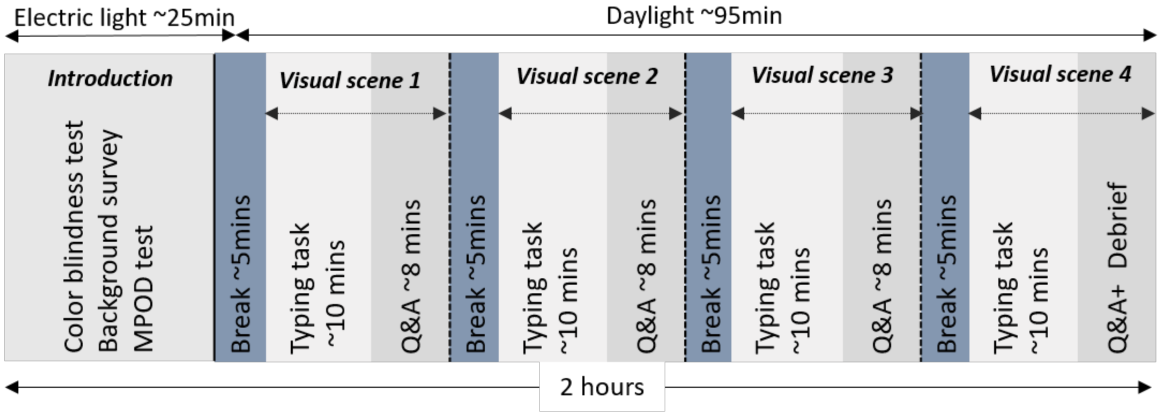

Figure 8-5 Experiment Procedure

8.3.6 Survey Questionnaire

Participants answered three survey questionnaires during the experiment:

i) Background questionnaire (about demographics, current emotional and physical state, indoor comfort preferences asked at the beginning of the experiment)

ii) Comfort questionnaire (about thermal comfort, discomfort glare, lighting levels, and color perception asked after every exposure)

iii) Debriefing questionnaire (about view quality, comparative feedback on four scenes, overall feedback asked at the end of the experiment)

Table 8-2 Questionnaire items asked after every exposure

Category	**Question**	**Response labels**
Open-ended	1. Is there anything about the physical environment that disturbs you in this moment?	Text
Thermal comfort	2. At this precise moment, how are you feeling?	Cold –Cool –Slightly cool – Neither cool nor warm –Slightly warm –Warm –Hot
	3. How satisfied are you with the thermal situation in this room?	Very dissatisfied – Dissatisfied – Neither dissatisfied nor satisfied – Satisfied – Very Satisfied
Visual comfort/ Glare	4. Are you experiencing any discomfort due to glare at the moment?	Yes- No
	5. At the moment, how would you describe glare in your field of view?	Imperceptible – Noticeable– Disturbing – Intolerable
	6. How much discomfort due to glare are you experiencing at the moment?	Not at all – Slightly – Moderately – Very much
	7. On a scale of 0-10, how much discomfort due to glare are you experiencing at the moment?	Not at all 0-1-2-3-4-5-6-7-8-9-10 Very much
Color perception	8. The colors of object inside the room looks natural	1-Strongly disagree -2-3-4-5-6-7-Strongly agree

In this section, we will only provide details about the questions that were ultimately analyzed in our study (cf. Results section) i.e. that either pertained to color perception or to thermal and visual comfort. These are listed in table 8-2. The questions and response labels were adapted from past studies with the aim to minimize the potential response bias (Chinazzo, 2019; W. Osterhaus & Bailey, 1992; Pierson, 2019a). The order in which the questions were asked was randomized in the survey to avoid any order bias (Fotios, 2009). These questions were answered on either a binary scale, a Likert (ordinal) scale, or a linear scale, or in one case as a free text, as specified in table 8-2.

The first survey question was an open-ended text field (Table 8-2, question 1) that allowed participants to report any disturbing sensations without forcing them to select from pre-defined options or drawing their attention to a particular comfort parameter (Pierson, 2019a). We evaluated answers to this question to check whether participants spontaneously mentioned glare in their answers since this was the main independent variable in the tested conditions. Thermal comfort and color perception (Table 8-2, questions 2&3,8) were evaluated only for ensuring that they were not causing any confounding effects on our main variables of interest (i.e. discomfort glare). Discomfort glare was the main independent variable that was evaluated on four different scales (Table 8-2, questions 4-7) to check and ensure the internal consistency of answers and the reliability of the questionnaire items.

8.3.7 Data cleaning and processing

We applied data filtering rules to ensure that all the experimental conditions had stable weather conditions and an unobstructed view of the sun within the participants' FOV. We discarded data points where the deviation in measured global horizontal irradiance (GHI) was more than 25% ((GHI_{max} - GHI_{min})/GHI_{mean}) over the duration of a participant's exposure to the whole session. We also discarded the data where the sun was hidden by a window frame or by any other object in the participants' FOV (checked by visual inspection of the HDR images). After cleaning the data, we were left with a total of 205 datapoints (102 with low transmittance and 103 with high transmittance) by discarding 8.5% of the data from the initial dataset of 224 points (~56*4). The final 205 datapoints consist of 50 points in blue conditions, 52 points in green conditions, 53 points in neutral conditions, and 50 points in red conditions. This distribution fulfilled our criteria of having at least 50 points (see section 8.3.1) in each color category.

The images of the scene were captured in ".pf" (picture float) format and were converted to ". hdr" format. HDR images were then processed using the Evalglare tool (version 3.03) (Wienold & Andersen, 2016) to calculate the glare metrics corresponding to the viewed scenes. We extracted the sun disc luminance (cd/m^2) from the HDR images by selecting the highest pixel value. The glare metric values (DGP and CGI) were calculated based on the default Evalglare algorithm that considers a threshold of 2000 cd/m^2 for glare source detection. The measured spectral data were processed by using the color package (Mansencal et al., 2022) of Python 3.9.

8.3.8 Statistical analysis

We used descriptive statistics to summarize the measured and HDR-derived physical quantities associated with each experimental condition. Descriptive statistics included mean, median, standard deviation, scattered boxplots, stacked bar plots, and line plots. Cronbach's alpha (Cronbach, 1951) was used to check the internal consistency between the participants' glare responses on different questionnaire items. To determine the effect of color on glare perception, we performed non-parametric pairwise comparisons between colored conditions by applying a Wilcoxon signed rank test (Wilcoxon, 1945). The Wilcoxon test was chosen over the Kruskal-Wallis test (Kruskal & Wallis, 1952), since Kruskal-Wallis can only determine if there is a significant difference between groups, but cannot determine which pairs of groups are different. We conducted multiple pairwise comparisons between the four colored scenes by applying a Bonferroni correction in which the p-values were multiplied by the number of comparisons. The Bonferroni correction was chosen over other methods because it has a stricter criterion and can be applied without any distributional assumptions of the data (Cabin & Mitchell, 2000; Field et al., 2012). We relied on Cohen's effect size thresholds to determine the strength of the correlation between two variables, where correlation coefficients > 0.3 were categorized as a moderate effect, and > 0.5 as a strong effect (Cohen, 1977).

8.4 Results

8.4.1 Thermal comfort evaluations

To maintain adequate thermal comfort, we kept the indoor temperature within comfortable ranges of 21 ± 2°C. Past studies have shown that glare perception can be influenced by thermal discomfort (Garretón et al., 2015) and the color of daylight can influence thermal comfort (Chinazzo et al., 2018). Thus, to confirm that the thermal conditions were not creating any unwanted biases, we analyzed the participants' responses to thermal comfort questions (questions 9 and 10 in Table 8-2). On the ASHRAE 7-point scale of Cold to Warm, 92% of participants reported either "Neither cool nor warm" (41%) or "Slightly warm" (36%) or "Slightly Cool" (15%) whereas only 8% reported either "Warm" (6%) or "Cool" (2%) and no one rated the two extreme ends "Cold" or "Hot". On the thermal satisfaction scale, 91% answered either "Satisfied" (61%) or "Neither Satisfied nor Dissatisfied" (30%) whereas only 9% rated "Dissatisfied". Therefore, a majority of participants considered thermal conditions as comfortable. Additionally, there were no significant differences in thermal comfort between the four colored conditions. These results confirm that thermal comfort was maintained in the experiments and there is thus a minimal risk of bias imputable to thermal conditions.

8.4.2 Color perception and spectral evaluations

The spectral characteristics of the conditions experienced by the participants are described by the measured SPD of the sun disc visible to the participants combined with the CCT and SPD measured at the participants' eye level. The variations in mean measured CCT values between scenes (cf. Table 8-3) follow the color of the 'sun window': the conditions associated with the blue glazing have the highest CCT whereas conditions associated with the red glazing have the lowest CCT. The CCT values are actually driven more by the sun's luminance which is almost 10 times higher in high transmittance conditions compared to low transmittance conditions. Therefore, the CCT measurements may not represent the color perception of the participants which can be confirmed by analyzing subjective votes on the color perception questions.

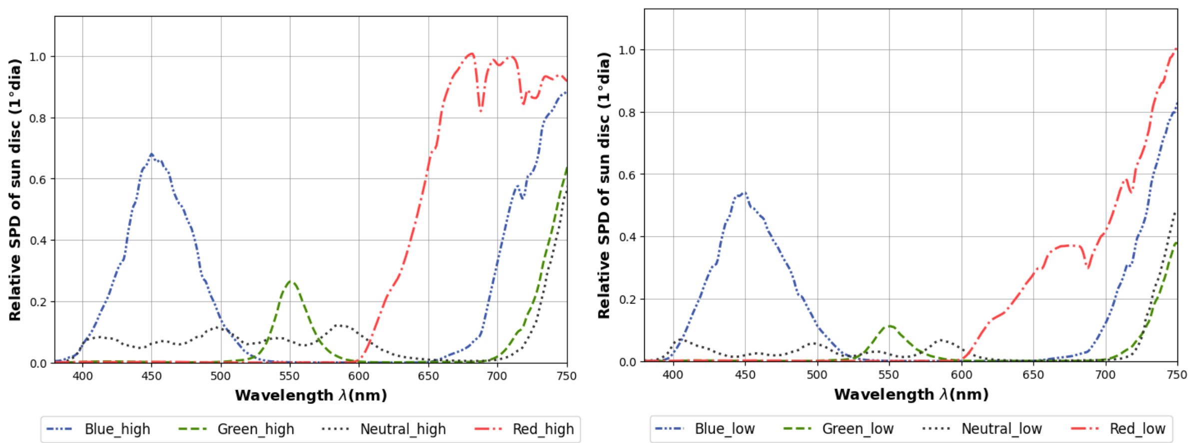

Figure 8-6 Mean relative SPD of sun disc measured at 1-degree diameter around the sun disc for eight experimental conditions, left: conditions with high glazing transmittance, right: conditions with low glazing transmittance

The mean value (at each wavelength) of the relative SPD of the sun disc (normalized to 1) measured for all sessions once classified by color and transmittance level are plotted for each of the eight experimental conditions in Figure 8-6. The SPD of the sun was measured as an integral of 1° diameter circling the sun disc which is approximately twice the size of the actual sun disc (∅=0.533°). As expected, the SPD of the sun follows the 'sun window' spectral transmittance curve shown previously in figure 8-3. It should be noted that the total irradiance under the visible spectrum varies between conditions: while the photometric units were kept similar between conditions, the corresponding radiometric units were, by definition, not. Figure 8-7 shows the mean values, at each wavelength of the different spectral irradiance measured at the participants' eye level for all sessions, categorized again by color and transmittance level. Unlike figure 8-6, in figure 8-7 the impact of SPD of sun disc is attenuated due to the contribution of daylight coming through the color-neutral 'view windows', which was our strategy to preserve the naturalness of indoor elements by changing only the color of the sun window. This is further reflected in the participants' responses to the color perception question (Table 8-2, question 8), where 88% of the participants rated the naturalness of color in the space as 6 or above on the 7-point scale (1-strongly disagree to 7-strongly agree). We can conclude that by maintaining enough color-neutral windows on the façade (all except the 'sun window'), we were able to avoid any risk of potential bias due to color distortion.

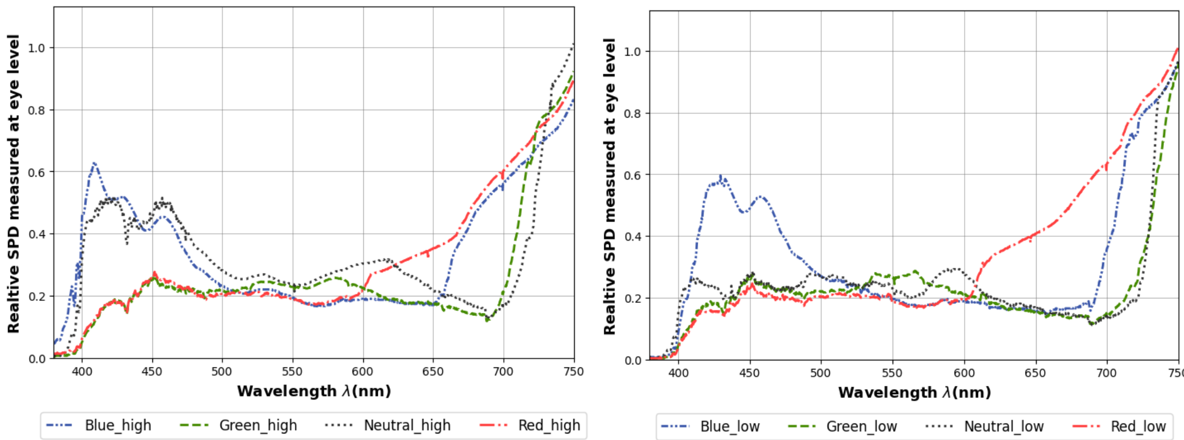

Figure 8-7 Mean relative SPD measured at participants' eye level for eight experimental conditions, left: conditions with high glazing transmittance, right: conditions with low glazing transmittance

8.4.3 Discomfort glare evaluations

8.4.3.1 Photometric characteristics of experiment conditions

To be able to evaluate the main effect of our study, namely that of color on glare perception, we first need to ensure that the daylight conditions were similar enough between the colored scenarios and within a scene exposure shown to every participant and therefore, color is the only quantity that varied within participants.

For this evaluation, we relied on the measured (E_v) and HDR-image-derived values (sun luminance, DGP, CGI, position index, and viewing angle) associated with the eight scenes as listed in Table 8-3. First, we validated the accuracy of the HDR images by comparing the image-derived vertical illuminance values to the measured vertical illuminance values. The RSME between the measured and the image-derived values was found to be 78 lux (7.4% when normalized) with a normalized bias of 7.5%., indicating good-quality images. Therefore, we can reliably compare the experimental conditions based on HDR image-derived quantities.

As reported in Table 8-3 and further illustrated in figures 8-8 and 8-9, we were able to achieve very similar mean values of the E_v, sun luminance, CGI, DGP, and position indices; viewing angle to the sun was also very stable between the colored scenarios in each category of low and high transmittances.

Table 8-3 Mean values of the quantities measured directly and derived from the HDR images for the eight experimental conditions

Experiment Scene	Sample size	Mean CCT (in Kelvin)	E_v (in lux)	Sun luminance (million cd/m^2)	DGP	CGI	Position index	Viewing angle
			Mean (SD)					
Blue_low	25	17790	1115 (109)	3.43 (0.57)	0.38 (0.016)	38.7 (1.66)	2.8 (0.70)	26.5 (5.32)
Green_low	26	6350	1100 (140)	3.89 (0.50)	0.38 (0.02)	39.5 (2.09)	2.8 (0.74)	26.7 (5.26)
Red_low	25	5160	1035 (120)	2.48 (0.27)	0.36 (0.019)	37.3 (2.11)	2.7 (0.76)	26.2 (5.43)
Neutral_low	26	6890	1090 (127)	3.41 (0.46)	0.38 (0.017)	39.5 (1.87)	2.7 (0.62)	26.7 (5.36)
Blue_high	25	18926	2290 (129)	22.1 (4.26)	0.50 (0.02)	48.7 (1.76)	2.8 (0.52)	26.9 (3.95)
Green_ high	26	6060	2430 (169)	26.1 (4.15)	0.51 (0.02)	49.3 (1.96)	2.8 (0.51)	26.8 (4.26)
Red_ high	25	5240	2350 (133)	22.3 (3.08)	0.50 (0.02)	48.9 (1.73)	2.8 (0.51)	27.0 (4.38)
Neutral_ high	27	7970	2370 (143)	25.8 (4.42)	0.51 (0.02)	49.5 (2.09)	2.8 (0.70)	26.6 (4.77)

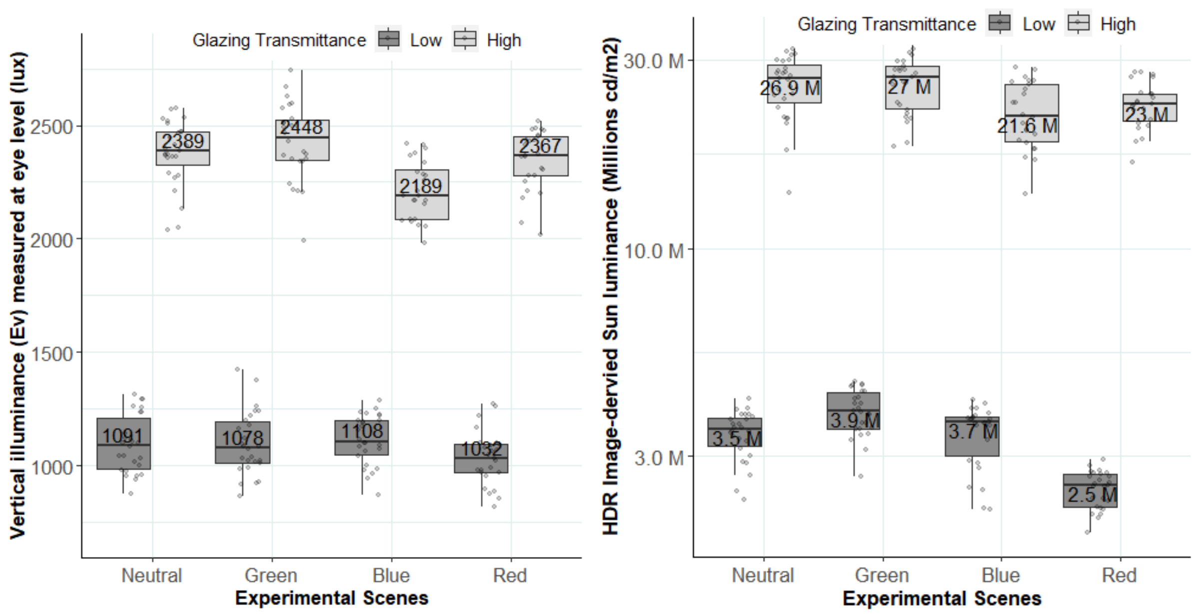

Figure 8-8 Scattered boxplots with median values. Left: Measured vertical illuminance at eye level. Right: HDRI derived sun luminance for eight experimental conditions.

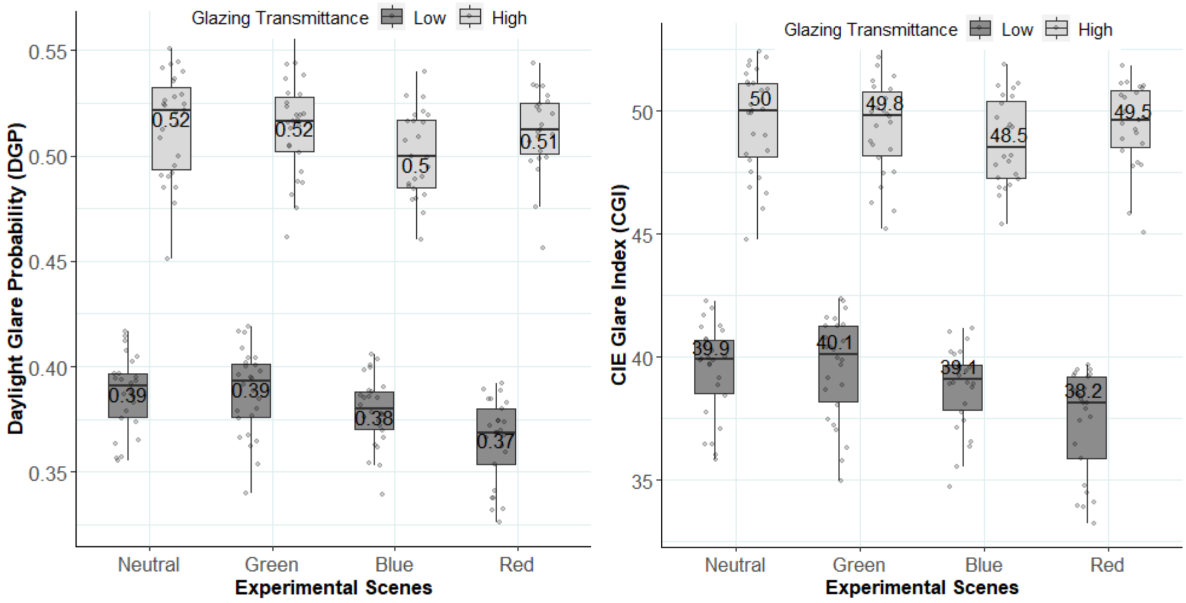

Figure 8-9 Scattered boxplots of glare metrics with median values. Left: Daylight Glare Probability (DGP). Right: CIE Glare index (CGI) for eight experimental conditions.

Figure 8-8 (left) shows the boxplots with median values of measured vertical illuminance at eye level for the eight experimental conditions. The distribution of vertical illuminance measured over multiple experiment days for all the participants have minimal variations (as also shown by Mean and SD in Table 8-3) between the four colors shown to every participant. However, slightly lower levels can be seen in the Blue_high and Red_low whereas slightly higher levels are found in Green_high condition compared to all the others. This can be explained by the slight differences in their colored glazing transmittances (cf. Table 8-1). We should note, however, that the mean difference in E_v between the scenes remains as low as 15.7% i.e., not enough to be noticeable subjectively since a change by at least 1.5 times is required to create a difference in lighting perception (International Commission On Illumination (CIE), 2002; Zhang et al., 2022). Therefore, we conclude that the conditions are comparable in terms of vertical illuminance at the eye.

We can observe similar variations in sun luminance and glare metric values (CGI and DGP) in Figure 8-8 (right) and Figure 8-9 (left and right). Out of these three quantities, the most noticeable difference is in fact observed in the sun luminance values for the Red_low condition, owing to its slightly lower glazing transmittance (cf. Table 8-1). However, when comparing the conditions in terms of CGI and DGP values, these differences become very small and conditions largely overlap with each other. As per the glare thresholds derived in a published cross-validation study (Wienold et al., 2019a), a difference of at least 8% in CGI and 11% in DGP is required to change glare response by one category on a four-category scale. In our study, the maximum observed difference in glare metric values (both CGI and DGP) is less than 8% between the scenes shown to any given participant, the conditions can be considered comparable.

8.4.3.2 Participants' responses

Figures 8-10 and 8-11 provide the participants' responses to discomfort glare questions for eight experimental conditions in the form of stacked bar plots. First, we analyzed the answers to the open-ended question (Table 8-2, question 1) and found that amongst the participants who reported "Yes" to the binary question (Table 8-2, question 4), 73% of them had written either glare or sun or bright light or colored light as a disturbing factor in their answers. The spontaneous mentioning of glare – or the use of words related to it – thus confirms that glare was a noticeable environmental factor. On the other hand, we found an excellent internal consistency (Cronbach's alpha=0.94) between the participants' answers to the three discomfort glare questions (Table 8-2, questions 5-7). Therefore, we decided to focus the analysis only on the responses received to questions 4 and 5, which are in fact also often used questions in discomfort glare studies (Karmann et al., 2022; Pierson, Piderit, et al., 2021; Wienold et al., 2019a).

In Figure 8-10, we can observe a clear difference in the participants' glare responses between the four colored scenes, whether for high or for low levels of glazing transmittances. This was actually not expected and was surprising, (except for the differences between blue and neutral which was hinted at by past studies (Jain et al., 2023)) since the calculated glare metrics were rather similar between the four colored scenarios, and made us expect that similar levels of glare would be reported too. On the contrary, participants experienced glare more often under red and blue conditions compared to neutral and green in both low and high transmittances. More specifically, the Green_low scene was rated as the most comfortable for the low transmittance conditions (Figure 8-10, left), while the Red_low scene was rated as the least comfortable with 41% more participants experiencing glare than for Green_low. Similarly, for high transmittance conditions (Figure 8-10, right), Neutral_high was rated as the most comfortable while Red_high was considered the least comfortable, this time with all participants reporting discomfort from glare (i.e. 52% more participants than for Neutral_high). The differences in glare perception are thus much higher between the neutral or green and the blue or red than when comparing green to neutral or blue to red. We can still note that high transmittance conditions have, in general, a higher percentage (16% more) of participants experiencing glare compared to low transmittance conditions, which was expected due to the higher glare source luminance resulting in higher values for the calculated glare metrics. Finally, comparing the trend of glare responses between the four colors, we could also observe a similarity under low and high glazing transmittance conditions, except for the green color which was rated most comfortable in low transmittance but second to neutral in high transmittance, although the difference is not significant.

Figure 8-11 shows the participants' responses on a four-point ordinal response scale ranging from imperceptible to intolerable glare. Again, we can observe a similar trend in glare responses as for the binary scale: participants were overall more disturbed by glare under blue and red scenes compared to green and neutral ones. For low transmittance conditions, Red_low was the most disturbing condition with 48% of participants disturbed by glare, which was much higher than in the Green_low conditions where only 4% of participants were disturbed by glare. The most disturbing conditions under high transmittance were again associated with Red_high, in which 88% of participants reported disturbing or intolerable glare. In contrast, only 22% and 23% of participants reported disturbing or intolerable glare under Neutral_high and Green_high conditions respectively. Blue conditions also had a higher percentage of participants disturbed by glare compared to neutral and green conditions, which follows the findings from a previous study where blue EC glazing was found to create higher discomfort glare compared to color-neutral glazing (Jain et al., 2023).

Overall, when combining the datasets of low and high transmittance conditions, the percentage of participants who reported disturbing or intolerable glare was 14% for the green glazing, 22% for the neutral one, 42% for the blue one, and 69% for the red glazing, making the red glazing the least comfortable and the green glazing most comfortable one (even more than neutral, though not significantly so as will be discussed in section 8.5.3). In other words, the number of participants getting disturbed by glare with the red glazing was approximately five times higher compared to the green glazing and three times higher compared to the neutral glazing. As far as the blue glazing goes, participants experiencing disturbing glare were three times more numerous than with the green glazing and two times more numerous than with the neutral glazing. Along the same lines, the median glare rating on the 0 to 10 numerical scale (Table 8-2, question 7) was 6 for the red scenes, 5 for the blue scenes, and 2 for both the green and neutral scenes.

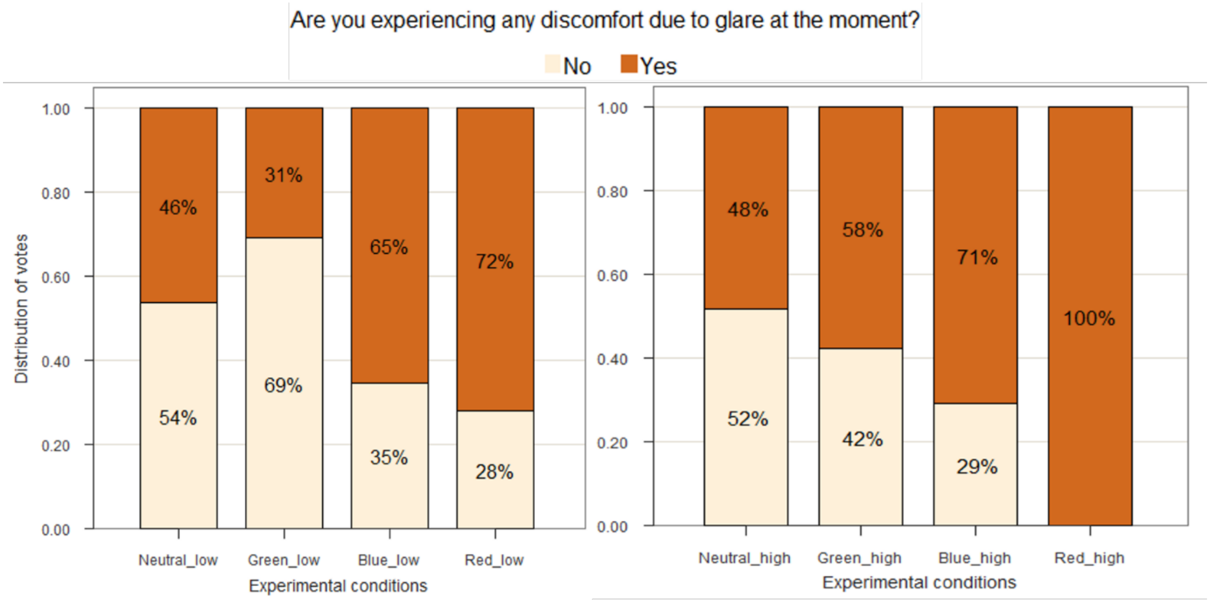

Figure 8-10 Participants' responses to discomfort glare on binary response labels. Left: conditions with low glazing transmittance. Right: conditions with high glazing transmittance.

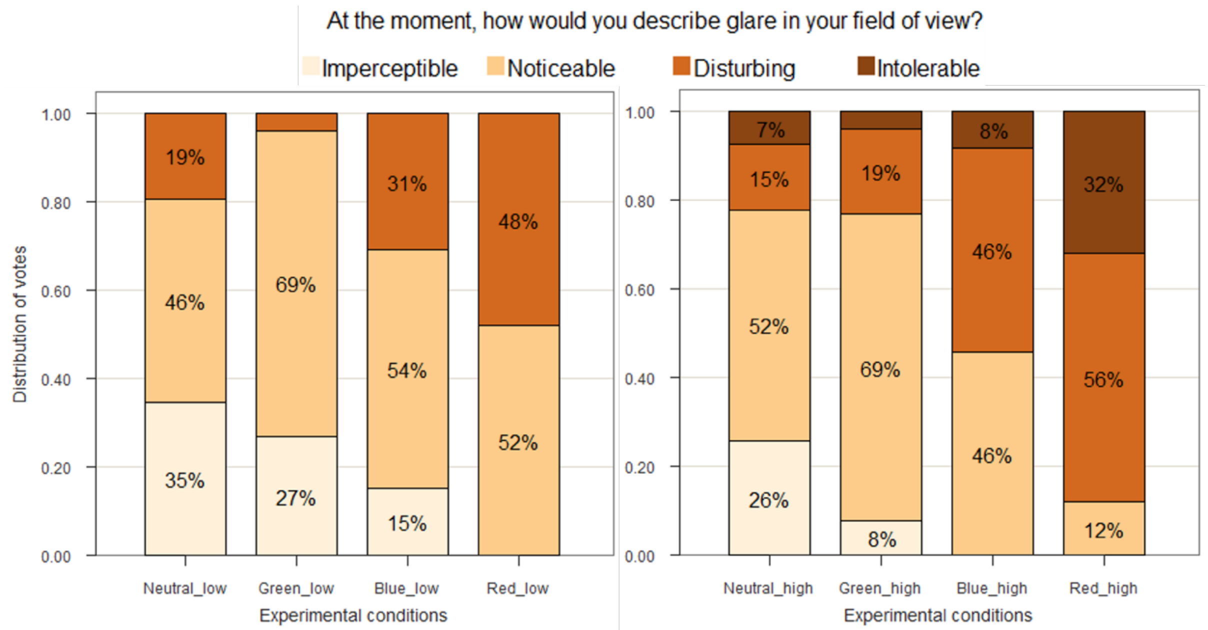

Figure 8-11 Participants' responses to discomfort glare on four-point ordinal labels. Left: conditions with low glazing transmittance. Right: conditions with high glazing transmittance.

8.4.3.3 Statistical differences in glare perception between the four colored conditions

From the descriptive statistical evaluations, it is already clear that participants did not perceive the colored conditions equally in terms of discomfort glare, despite the conditions being associated with similar glare metric values. To check the statistical significance of the differences in glare perception between the four colors, we conducted pairwise Wilcoxon signed rank tests on the full sample size. Table 8-4 presents the results from the Wilcoxon test with the Bonferroni adjusted p-values (=p-values*6), effect sizes (Z statistic), and their interpretation based on Cohen's thresholds. The mean differences between the glare responses were statistically significant with a large effect size for the following pairs: Neutral- Red ($p<0.001$, effect size=0.53) and Green- Red ($p<0.001$, effect size=0.57), with of course a higher mean in Red scenes compared to Neutral and Green scenes. The pairs Neutral-Blue and Green-Blue also had statistically significant differences in glare perception, but with a moderate effect size ($p<0.05$, effect size=0.30). We did not find statistically significant differences between the Neutral-Green and Blue-Red pairs. These inferential statistics further confirm the results indicated by the bar plots in the previous section.

Table 8-4 Results of pairwise comparisons in glare perception between the four colored conditions

Group1	**Group2**	**n1**	**n2**	**p-value**	**p-value (Bonferroni adjusted)**	**Effect size**	**Magnitude**
Neutral	Green	53	52	0.977	1	0.05	small
Neutral	Blue	53	50	0.002	0.012	0.30	moderate
Neutral	Red	53	50	3.31E-07	1.99E-06	0.53	large
Green	Blue	52	50	0.002	0.01	0.31	moderate
Green	Red	52	50	2.61E-07	1.57E-06	0.57	large
Blue	Red	50	50	0.011	0.065	0.26	small

8.5 Discussions

The results found in this study are somewhat unexpected and therefore interesting for a number of reasons. The results do not follow the glare metrics' predictions i.e. the discomfort glare was not perceived equally for conditions having similar glare metric values but different colors. This can at least in part be explained by the fact that existing glare metrics do not incorporate spectral characteristics of the glare source and only differentiate glare sources in terms of luminance values, derived using the CIE $V_{2^\circ}(\lambda)$ function. The $V_{2^\circ}(\lambda)$ function peaks in the mid-wavelength region at 555nm and is least sensitive in the short- and long- wavelength regions. Yet it was for glare sources having SPD dominant in the short- or the long- wavelength regions that we found the highest sensitivities to glare. It can thus be concluded that $V_{2^\circ}(\lambda)$ is *not* representing correctly the human eye's spectral sensitivity when a high-intensity colored glare source is in the field of view. This reinforces the need for modifications of the normalized spectral sensitivity functions in such conditions. For that reason, the spectral weighting for glare evaluations in such situations needs modifications.

Our results also depart from findings reported in past user studies that reported similar discomfort glare from white, green, and red LEDs of equal luminance (Bullough, 2009; Fekete et al., 2010; Kimura-Minoda & Ayama, 2011; Yang et al., 2016), which, in their case, was consistent with existing glare models. As all the previously proposed discomfort glare spectral sensitivity functions ($V_{DG}(\lambda)$) have a higher weighting in the short-wavelength region compared to $V_{2^\circ}(\lambda)$ and a similar weighting in the mid- and long-wavelength regions as $V_{2^\circ}(\lambda)$, they cannot describe the glare perception results found in our study, especially not those we got under the red conditions. Looking for an explanation, we can note that there was a unique factor in our study, namely the use of daylight – and more specifically of light coming directly from the sun disc and filtered through colored glazing – as the only source of glare. Besides the much higher intensity, it has a significantly different SPD to the much narrower-band SPD of the colored LEDs used in previous studies, we can wonder whether this might be an explanation for the difference in glare perception reports between our and these other studies. An addition factor may be that our participants did not receive a truly constant SPD during their exposure to a given condition since daylight naturally exhibits continuous temporal and spatial variations over time, to a greater extent than electric light sources. Finally, we should also remember that the SPD recorded at the participants' eyes (shown in Figure 8-7) are actually a combination of the SPD of the colored "sun window" filtered sun disc and of daylight entering though the color-neutral 'view windows', a feature that is again different from these past studies. More research would, however, be needed to determine whether these differences are the most plausible explanation of the inconsistency between our and these former studies.

To investigate this a little further, we conducted a preliminary check to see whether the participants' gaze behavior might have been influenced by the color of daylight since this was the only independent variable in the experiment. More specifically, we were wondering if color might have impacted their subjective glare assessment by making them spend more or less time looking directly at the glare source in some color conditions. The gaze data was extracted from video recordings of the participants' faces captured during their exposure to a given color condition by resorting to an open-source deep learning algorithm named OpenFace (Baltrusaitis et al., 2018). Although, the algorithm had some limitations in accurately predicting gaze in certain scenarios which led to the removal of a substantial amount of gaze data. The preliminary analysis done on the remaining data does not seem to indicate any strong difference in the participants' gaze behavior between the different colored scenes.

For developing glare metrics that would more reliably be able to predict discomfort under colored daylight conditions, it would be necessary to extend this study to a larger variety of colored stimuli with daylight as the glare source. It is also essential to understand to what extent a glare source's SPD or apparent color contributes to glare perception, as we do not know whether the current findings could be extended to colored façades having similar color appearances but different SPDs and vice versa. A recent study has actually found that LEDs having the same color appearance (quantified in that study as corresponding to a CCT of 7000K) but different SPDs – differing especially in the blue region – created the same level of glare perception in the study's participants (Huang et al., 2018). Based on this, we could hypothesize that color appearance matters more than the SPD of a glare source when it comes to glare perception. However, these findings cannot simply be extended to daylight conditions due to its complex and dynamic nature. Thus, a promising starting point for future studies investigating the potential interactions between color or SPD and glare would be to rely on daylight-induced stimuli with different SPD but with the same color appearance.

8.6 Limitations

The main limitations of this study, which may have a significant impact on the generalizability and accuracy of the results, include the following:

- The results obtained are only valid for the filtered daylight spectrum being tested. These aspects of daylight will change depending on many factors including glazing properties, climate, and location, for which different results can be expected.
- The commercially available colored glass facades are likely to be different than the glazing used in this particular study when it comes to spectral characteristics and color appearance, and this difference may influence glare perception. Future research could address this limitation by conducting experiments with less saturated colored glazing, and with glazing technologies more commonly found on the market.
- This study was limited to one desk position placed so as to have the sun in the central field of view. Different results should be expected for different seating positions in relation to the window since color perception has been shown to vary across the visual field (Hansen et al., 2009). We also acknowledge that while the seating position used in the study is not recommended for office environments, it provided the most critical condition for glare evaluation, which was the objective of this study.
- 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. With age, the spectral sensitivity of the human eye has been shown to change (Curcio et al., 1996). Therefore, the results do not apply to individuals of higher age groups and/or with certain vision limitations.

8.7 Conclusions

In this study, we evaluated the effect of the color of sun disc filtered through saturated-colored glazings on discomfort glare perception. Participants were exposed to four conditions that had similar sun luminance, a similar apparent sun position relative to their FOV, and similar E_v but varied in the color of sun disc as a result of its filtering through red-, green- and blue-colored as well as color-neutral glazing. Based on the participants' subjective votes, we found that color had a strong influence on their glare responses ($p<0.001$). Participants perceived glare more often from the red and blue colored conditions compared to neutral and green colored ones. The percentage of participants getting disturbed by glare was 69% for the red glazing, 42% for the blue one, 22% for the color-neutral glazing, and 14% for the green one. In comparison to the color-neutral as well as the green glazing, the red glazing had at least three times more, and the blue glazing had at least two times more participants getting disturbed by glare. We found both statistical and practically significant differences in glare perception between the neutral or green and either of the other two colored conditions (red or blue).

These results confirm a strong dependency of glare perception on the color of the glare source, as had been previously shown in studies on colored LEDs. However, the highest glare perception found under the red glazing was unexpected since none of the previous studies reported red LEDs to be more disturbing than other colored LEDs. The key difference in terms of the study protocol is the use of the sun as a glare source in our study. These results also call for an update to existing glare metrics so as to extend their applicability to colored daylight conditions and replacement or modification of the $V(\lambda)$ weighting in their equations. But to include the color of the glare sources in glare models, we first need to extend the current work to include a larger range of colored stimuli and understand better how glare perception varies under a broad range of colored conditions. For example, glare perception under yellow, orange, and purple colors, which are complementary to those used in the present study, could be an interesting option to investigate the influence of colored daylight on the spectral sensitivity of the human eye. An important finding of this study overall is that discomfort glare can probably be minimized by avoiding (saturated) red and blue colors. This finding can provide more nuanced development goals for electrochromic glazing coatings and colored glazing in general and support a more comprehensive view of the integration of colored PV panels in façades by offering a complementary perspective pertaining to visual comfort.

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Key outcomes of this study are:

- Participants perceived glare more often from the red and blue colored conditions compared to neutral and green colored ones- red was most disturbing whereas green was most comfortable in terms of discomfort glare.
- Findings suggest that V(λ) is not suitable to characterize luminance under brightly lit colored daylight conditions, therefore, the spectral weighting in glare models need modifications for such conditions.
- Glare from the sun disc filtered by red colored glazing was *surprisingly* perceived most discomforting, since none of the past studies with electric light reported strongest glare from red LEDs.
- Results also provide future directions for glare model developments to include the effect of color of daylight on glare perceptions.

PART IV : CONCLUSIONS

Chapter 9

Conclusions

Chapter 9

Conclusions

The work presented in this thesis aimed to broaden the current understanding of discomfort glare and to improve its evaluation in indoor daylit spaces by investigating factors likely to influence glare but not yet included in existing prediction models. More specifically, the objectives of this thesis were to determine the influence of physiological and environmental factors on discomfort glare perception: macular pigment optical density in the retina and the color of the sun disc resulting from colored glazing towards the sun. For this purpose, we conducted three user studies over four years during three consecutive winter periods (2019-2022) in Lausanne, Switzerland which involved a total of 131 human participants.

The following sections outline the key findings of the thesis concerning each of the two investigated factors, the novel contributions that have been made, possible future research avenues, and outlook:

9.1 Contributions and impacts

9.1.1 Influence of macular pigment on discomfort glare

In the first part, we investigated the influence of macular pigment density in the retina on discomfort glare perception under indoor daylight conditions with the sun as the glare source. Based on the literature review, MPOD seemed the most promising factor that was hypothesized to partly account for the existing inter-individual variability observed in discomfort glare perception. The influence of macular pigment on discomfort glare has only been studied in ophthalmological laboratory settings and has not yet been investigated in indoor daylit working spaces.

Based on this gap, the research question that this part aimed at answering was "*what is the influence of macular pigments on discomfort glare from electric light and daylight?*"

This question was answered by following a psychophysiological approach in which the measured macular pigment density was compared with participants' glare sensitivity which was evaluated first in electric lighting conditions and then in normal daylight office settings with sun disc seen behind a color-neutral glazing in one study and a blue-colored glazing in another study. Additionally, participants' certain structural and functional aspects of the retina (retinal thickness and photostress recovery time) concerning the macula were measured in the ophthalmic hospital.

We evaluated discomfort glare perception under daylighting and compared it to measured ocular parameters, namely, MPOD, retinal thickness and photostress recovery time (Chapter 5). The participants' glare perception was evaluated from the sun disc filtered by color-neutral glazing and saturated blue-colored glazing (dominant wavelength 445nm) in the near-peripheral field of view (~30°).

Comparing participants who did experience glare to the ones who did not report any glare in the color-neutral scenarios, we found no significant difference in their measured MPOD values. Similarly, measured photostress recovery time and retinal thickness had no significant influence on the participants' glare perception with color-neutral glazing either. In other words, all the measured ocular factors were not significantly different between the less sensitive and more sensitive groups of participants categorized based on their glare perception. This finding thus departs from prior literature, which established an influence of MPOD in glare reduction in ophthalmological lab settings. Though, this could be expected owing to the experimental conditions that were applied in our studies, in which the sun disc filtered by the neutral glazing did not have a strong short wavelength component (which is absorbed by MP) like past studies and also the sun was not particularly close to the fovea within the participants' FOV where macular pigments are most concentrated.

With blue glazing however, we did find a statistically significant correlation ($p<0.01$, $r=0.40$) between MPOD and the participants' glare perception: participants with higher MPOD tended to report glare less frequently than participants with lower MPOD values. This finding is surprising since in our study glare source is not close to the fovea where macular pigments are most concentrated. In literature, studies that found an impact of MP on visual discomfort always had the glare source close to the fovea (within 6°). Therefore, it can be hypothesized that in our study participants' free gaze behaviour unlike past studies might have caused instances where the sun was in fact close to the fovea.

To further look into this hypothesis, we estimated that throughout each experimental session, the participants' average gaze direction varied from +10 degrees to -15 degrees in the vertical direction based on the recordings of their faces during the exposure which were processed in a deep learning model (Baltrusaitis et al., 2018). This gaze behavior indicates that even though the glare source (sun) was not projected in the fovea, there may have been instances where the sun was closer to the fovea and therefore, where the attenuation through the macula may have been stronger.

Overall, the results demonstrate that MPOD cannot account for the inter-individual variability observed in discomfort glare perception for normal working scenarios (i.e. with free gaze behavior and glare source outside the fovea) under neutral daylight conditions, but can, in part, explain the variability when glare is perceived under saturated blue colored glazing. This finding should be further confirmed under EC glazing that exhibits blue color and is more widely used in buildings compared to the saturated blue glazing used in our experiment. To delve into this further, we compared the SPD of sun disc filtered by blue EC glazing and by saturated blue glazing used in our experiments to the absorption spectrum of the macular pigments (Figure 2-3) (additional publication (Jain, Wienold, et al., 2022). Appendix A.2). We found that the attenuation effect of macular pigment was higher for saturated blue glazing compared to the EC blue glazing owing to the narrower spectral shape of the saturated blue glazing. Therefore, indicating that the macular pigments might not have a strong impact on glare perception under blue EC glazing or less saturated blue glazing. This also demonstrates that the SPD of the light source plays a key role rather than the apparent color of the glare source in determining the strength of influence of macular pigments on glare sensitivity. However, this hypothesis should be further confirmed by a user study.

It should be noted that the sample population in our study was quite homogenous in terms of having a healthy macula and normal ocular health due to the strict inclusion criteria and many data-cleaning steps applied in our study. Therefore, in case of any ocular pathologies among the participants, the findings of this study will not be applicable.

Since we did not find any influence of macular pigment, retinal thickness, and photostress recovery on sensitivity to glare under neutral daylit conditions, it can be hypothesized that variations that exist in these parameters among the individual with a healthy macula do not contribute to the discomfort glare mechanism. This also strengthens that future studies should focus more on the visual pathways beyond macular pigments i.e. pathways concerning photoreceptors (cones and ipRGCs) and the neural pathways from photoreceptors to the brain. We discuss these possibilities further in section 9.2.

The results from this part can also be useful for glare prediction algorithms that would model the optical pathways. For such a model, it might be useful to increase their reliability and accuracy, by including individual macular pigment density when the glare sources are close to the fovea and exhibit a dominant emission in the shorter wavelength region. In such cases, individual differences in glare perception might indeed be in part explained by their varying levels of macular pigment density. A first step towards this has already started in the CIE- Technical Committee 3-57 on deriving *a generic discomfort glare sensation model* from a physiological viewpoint.

Overall, the results contribute towards advancing the knowledge on the role of macular pigments in discomfort glare mechanism and lead to valuable insights based on which future investigations can be conducted.

Methodological contributions

In regards to research methods, this thesis raises awareness for the necessity of conducting a pilot study to test the applicability of experiment protocol and questionnaires on which the core investigations can be based, which if not done properly can distort the findings. We followed a very rigorous procedure to clean both the measurement data and participants' ocular data that included several intermediate steps, to have a robust dataset on which the analysis can be based. The data cleaning procedure described in chapters in parts II and III can provide a useful workflow for future studies. Every step taken in the experiment protocol aimed at minimizing potential bias (cf. Table 3-1) was significant in achieving good quality data and therefore, in achieving reliable results on which future studies and glare prediction models can be based.

In psychophysical research, it is extremely challenging to reconstruct and quantify which physical parameters contributed most to the human perception of the environment (Bechtel & Churchman, 2002). In such cases, the additional evaluations such as the gaze behavior and head pose measured in our protocol proved to be valuable, in part relating certain subjective assessments to the physiological responses and providing insights on which further hypotheses could be made.

Additionally, the research approach used in our study highlights the importance of using more than one subjective method/questionnaire to evaluate glare. By asking the discomfort glare question on more than one scale, we were able to evaluate the inter-consistency between participants' answers and check their reliability. The findings indicate that all the glare scales evaluated in our user studies work equally well, therefore, confirming the reliability of the questionnaires and the protocol as well.

The research also highlights that for the field and laboratory glare studies conducted specifically under colored daylighting or electric lighting conditions, emphasis should be given to spectral measurements in addition to the luminance and illuminance measurements. Although it is extremely difficult to measure and control the light spectrum arriving at the retina due to the free gaze behavior in experimental setups. The advancements in wearable tech that can measure personal spectral lighting exposure (Stampfli et al., 2023) can be particularly helpful in user studies to measure daylight exposure.

9.1.2 Influence of color of daylight on discomfort glare

We investigated, for the first time, the influence of the color of the sun disc (filtered by colored glazing) on discomfort glare perception. Based on the literature review, the color of the light was identified as a factor most likely to influence discomfort glare but that had not been investigated yet in the context of the color of daylight. Given the increasing use of blue-tinted EC glazing and colored photovoltaics glass that causes spectral shifts in filtered daylight, it is worth studying the influence of the color of daylight on glare perception.

Motivated by this research gap, the main research question that this part aimed at answering was "*Does the color of daylight (i.e. sun disc filtered by a colored glazing) influence discomfort glare perception, and what the nature of this influence is?*"

This question was answered through three user studies conducted under a daylit environment in an office-like test room, one with blue EC glazing, one with color-neutral glazing, and the third one with red, blue, green, and neutral glazing. In all three studies, a similar methodology was followed where participants were exposed to four experimental conditions with the direct sun as the glare source visible in their field of view and reported their discomfort glare perception on survey questionnaires. During the exposure, only the window-pane facing the sun was manipulated while the others served to provide sufficiently enough daylight and as unchanged as possible in terms of color. In the case of user studies with EC and color-neutral glazing, the transmittance of glazing was manipulated in four conditions shown to the participants. While the user-study with colored glazing had experimental conditions with similar transmittance but different colors in each condition. The transmittances of the remaining window panes in all three studies were set in a way to keep the overall color rendering in the space as neutral as possible, and to not have any unwanted bias due to distorted color perception in the test room.

The results found by evaluating participants' responses not only answered our main research question but also provided several useful insights based on which hypotheses are made for future investigations. These findings, as discussed below, provide new knowledge on the spectral sensitivity of the human eye under saturated colored intense glare sources (=colored sun disc), and provide suggestions on modification of discomfort glare models. Findings also contribute to the building industry and daylight standards for achieving better visual comfort in indoor daylit spaces.

The results found in this thesis established, for the first time, that the color of sunlight (filtered by colored glazing) influences discomfort glare perception. First, the between-study comparison revealed that the glare was perceived more strongly in blue EC glazing compared to color-neutral glazing (Chapter 7). Afterward, the user study with colored glazing revealed that the glare was perceived more strongly in red and blue glazing compared to neutral and green glazing (Chapter 8).

We compared the relative differences in glare responses collected with the blue EC glazing to the glare responses collected with color-neutral glazing, to determine whether the color of the sun disc altered by the blue vs neutral glazing has any influence on the glare perception (Chapter 5). We found that the participants were better able to tolerate glare under color-neutral glazing, whereas they perceived it more strongly under blue glazing. These findings demonstrated that the color of a glare source can strongly influence people's glare perception under daylit conditions.

To include the effect of color in glare models, we modified the glare models based on four previously proposed spectral discomfort glare sensitivity functions which were based on the glare experiments conducted in electric light. The method adapted to calculate modified glare models included manipulating the luminance of colored sun discs by replacing the $V(\lambda)$ weighting with the previously proposed spectral weighting for discomfort glare. This was achieved by calculating the spectrum of the colored sun disc, based on standard ASTM spectra and measuring direct solar irradiance, visible behind the glazing. Comparing the modified glare metric in blue conditions to neutral conditions, none of the four modified glare models was found to be applicable to predict the glare perception for our experimental conditions under daylight. This, therefore, suggested that discomfort glare spectral sensitivity functions developed based on glare perception under electric light are limited in their applicability when implemented to anticipate the glare under daylight. This could be due to the spectral properties of the electric light with narrower distribution in comparison to daylight.

One limitation of this between-study comparison comes from the difference in stimuli range between blue and color-neutral conditions owing to the difference in glazing transmittance, therefore, the analysis relied here on relative comparison rather than absolute values. To further extend this investigation to other types of colored glazing, we decided to conduct the new user study using only saturated colored glazing.

In the next user study, we compared the glare responses under colored glazing (red, green, blue, and color-neutral) to determine whether glare from the differently colored visible sun created different levels of discomfort glare perception (Chapter 6). The four colored conditions were designed to correspond to similar photometric properties and spatial distribution of daylight by choosing similar visual transmittance properties for the window panes and keeping similar viewing directions towards the sun. What we found was a strong influence of the color of the glare source (=visible sun) on the discomfort glare perception, with more participants reporting glare in the red and blue conditions compared to the neutral and green conditions. The effect of color was found to be similar for two tested glazing transmittances.

The most surprising outcome was that the conditions with red glazing were rated as the most disturbing, even more than the blue ones. The number of participants reporting glare in red condition was approximately five times higher compared to the green glazing, three times higher compared to the neutral glazing, and 1.6 times higher compared to blue glazing. This was unexpected since almost all of the previous studies conducted with colored electric light consistently found blue LEDs to be the most discomforting while red, green, and white LEDs didn't have a significant difference in their reported glare ratings (Chapter 2, Table 2-2). This suggests that red-colored sunlight (as a result of filtering by red glazing having a long-wavelength dominated spectrum) may play a special role when it comes to glare perception that has not been investigated in any other study and therefore requires special attention.

To look for an explanation for this unexpected finding, we evaluated participants' gaze behavior (recorded using a webcam and extracted by an AI algorithm (Baltrusaitis et al., 2018)) during the exposure to four colored conditions to see whether the color might have impacted their subjective glare assessment by making them spend more or less time looking directly at the glare source in some of the color conditions. However, the preliminary analysis does not seem to indicate any strong difference in the participants' gaze behavior between the different colored conditions.

We also looked into the spectral discomfort glare sensitivity functions proposed in the literature to find some explanation for the red color is the most discomforting one. However, the previously proposed functions have similar weighting as $V(\lambda)$ in the mid- and long- wavelengths and higher weighting only in the short-wavelength region compared to $V(\lambda)$ (Yang et al., 2016). This is because the red-colored electric light sources were creating more or less similar perceptions of glare compared to green, white, and yellow light sources in the past studies.

These results confirm a strong dependency of glare perception on the color of the glare source, as previously shown by past studies on colored LEDs. However, the significantly high glare responses found for the red glazing depart from the literature and the results overall cannot be explained by the previously proposed spectral discomfort glare models. This finding revealed the less-known aspects of human spectral sensitivity under intense colored glare sources, which requires further investigations. It also requires redefining existing spectral sensitivity functions and therefore, modifying glare models which are based on such functions.

Applicability of existing glare models

We determined the applicability of existing daylight discomfort glare models in the experimental conditions evaluated in this thesis, which had low transmittance glazings and the sun in the field of view.

In the user study with EC glazing (Chapter 6), we evaluated the performance of five glare metrics (E_v, CGI, DGP, UGP, and DGI) in scenarios with two viewing direction-one parallel to the façade, another perpendicular to the façade, and three low glazing transmittances. We found that the contrast and hybrid effect-based glare metrics (CGI, DGP, UGP, and DGI) all performed quiet well in predicting glare perception when the sun is in the FOV, solely saturation effect-based glare metric (E_v) did not perform well in predicting glare in such scenarios with high contrast.

The results from colored glazing experiments found a strong influence of color on glare perception. The existing glare models cannot properly predict the influence of color on discomfort glare since they only rely on luminance weighted based on $V(\lambda)$ and do not account for spectral and/or color characteristics of the glare source. In other words, findings revealed that applying the existing $V(\lambda)$ functions cannot account for the color-effect found in the study. Based on the findings, we can hypothesize that only considering a spectral weighting function might not be the appropriate solution and the apparent color of the glare source should be considered as well by possibly using color-based appearance models. Results, therefore, call for an update to existing (daylight) glare models to extend their applicability to colored (day)lighting conditions. Further suggestions on future glare model development to include the effect of color are provided in section 9.2.

Practical implications

The findings of this thesis contribute to the building industry by providing development goals for the EC and colored BIPV panels for achieving better visual comfort. This research also contributes to the daylight standards in buildings by providing transmittance thresholds required for glare protection in typical office settings.

There are several exciting developments currently taking place in the glass façade industry, both in terms of material developments and in their applications in buildings. The research conducted in this thesis on EC glazing and colored façade, which suggests development goals for glazing manufacturers aimed at daylight glare reduction, is more relevant than ever.

The recent implementation of the decarbonizing act in the United States in August 2022 has added a new tax credit for dynamic electrochromic glass that can cover up to 30% of costs associated with the EC glass (*The Inflation Reduction Act (IRA)*, 2022). Similarly, many European countries are providing attractive incentives for the adoption of BIPV in buildings. The glass sector alone in the BIPV market is expected to have a value of USD 4 billion by 2026 and a growth rate of 40% in terms of their adoption in buildings (*Coloured BIPV*, 2019). These steps would further promote the smart glazing and BIPV systems by bringing them to cost parity with the traditional glazing and shading solutions and could result in large-scale adoption of such glazing into the buildings.

The research conducted in the EC user study (Chapter 6) has shown that at least a transmittance of 0.14% is required for glare protection with blue-tinted EC glazing when the sun is in the central field of view. Subsequently, a simulation study (cf. Appendix A.2) based on our findings was conducted to determine the EC glazing transmittance required for glare protection based on annual simulations in Rome, Frankfurt, and Stockholm (Wienold et al., 2022). It was revealed that an EC system that can switch up to a transmittance level of 1% works reasonably well for mitigating glare in typical office situations with viewing direction parallel to the window, in Frankfurt and Stockholm (mid and north European climate). While for Rome, which has a sunnier climate, a transmittance of around 0.5% would be necessary to achieve similar glare protection. The results based on the simulation study will help improve the "EN17037 daylighting standards in buildings" (CEN, 2019) and provide better glare control strategies for daylight optimization.

Our research has also shown that for the same transmittances, color-neutral glazing is better in controlling glare compared to blue-tinted EC glazing. Additionally, color-neutral glazing was rated more natural and was preferred in general compared to blue glazing. Although EC glazings with such low transmittances and color-neutrality are not widely available in the current market for large-scale applications, recent research on advance EC materials has demonstrated that it is plausible to achieve switchable glazing reaching up to 0.1% while improving the color-neutrality (Fleury et al., 2022; Lagier et al., 2021). Therefore, such solutions should be further investigated for their large-scale applicability. Additionally, some recent EC solutions (Halio, 2022; View glass, 2022) on the market are claimed to be color-neutral and can reach up to a transmittance of 0.1%. Such glazing systems are desirable and should be tested through user assessment studies to determine their performance for glare control.

The results have also shown that the red and blue colored façade creates higher discomfort from glare compared to the neutral and green façade. These findings can provide more nuanced development goals for colored glazing and support a more comprehensive view of the integration of colored PV panels in façades by offering a complementary perspective on visual comfort. These findings will also have benefits for architects and designers who can make informed design choices on the color of the façade by considering their influence on visual comfort.

9.2 Future research

More research is still necessary to further develop the understanding of the physiological rationale of discomfort glare perception and to extend the discomfort glare models to colored daylit scenarios. We propose two relevant future directions, to get closer to each of the objectives, based on the results of this thesis.

Investigations on inter-individual variability in discomfort glare

The research conducted in this thesis revealed that inter-individual variability in discomfort glare perception cannot be explained by the variability in macular pigment under naturally lit color-neutral conditions. Therefore, the question remains -*what are the factors responsible for causing the large inter-individual variability observed in discomfort glare perception?* Going back to the literature review (section 2.1.1.), this variability can be assumed to originate from the personal and physiological characteristics of the subject. It could be a combination of several such factors which would make it even more complex to solve. To understand this variability, it is important to first understand the physiological rationale of experiencing glare.

One of the less investigated factors for its contribution to physiological mechanisms in discomfort glare perception is ipRGCs. A recent study has suggested that melanopsin signals play a crucial role in the estimation of perceived brightness (Yamakawa et al., 2019). This becomes more interesting, specifically, in the case of blue-colored glare sources that create higher discomfort, at the same time have a higher impact on stimulating melanopsin. A recent study by Iodice evaluated the glare perception from two electric light sources of similar CCTs but different SPDs that create higher or lower stimulation of melanopsin (Iodice, 2020). The author found that subjects perceived higher discomfort under the condition having higher melanopsin sensitivity compared to the lower one, therefore, indicating a role of ipRGCs in glare perception. To our knowledge, this is the only study that systematically investigated the role of ipRGCs in glare perception. Therefore, studies investigating the role of ipRGCs, specifically in daylight conditions should be conducted.

Another parallel approach would be to focus on the neural pathways from photoreceptors to the visual cortex. Since the retina itself does not have any pain receptors and the discomfort and/or pain from the glaring light is processed in the brain, therefore, investigating the neuro-anatomical factors that relate to the pain sensation could provide useful insights. However, the methodology concerning such investigations is not a straightforward one. There is, so far, only one study by Bargary et al.(Bargary, Furlan, et al., 2015) that investigated cortical hyperexcitability as a result of glare sensations. Stone (Stone, 2009) proposed an interesting theoretical model of pain experienced as a result of light exposure based on the gate control theory of pain that views the transmission of pain as a complex response system with feedback control. Such conceptual models should be tested further to inform on the physiological mechanism of glare.

Extending the daylight discomfort glare models to colored daylit conditions

From our findings on the color part (part III), it is very clear that the glare models need to be updated to account for the influence of color on glare perception. This thesis has already revealed the glare perception that can be expected from the red, green, and blue-colored sun discs covering three distinct parts (short-, mid-, and long-wavelength regions) over the visible spectrum. However, developing a glare model that can accurately predict the glare perception under colored daylit scenarios requires several additional steps:

- The first step towards modifying the daylight discomfort glare models would be to extend this range further to a larger variety of colored stimuli with daylight as the glare source. For example, glare perception under yellow, orange, and purple colors, which are complementary to those used in the present study, could be an interesting option to evaluate.
- It should be determined whether the SPD of the glare source or the apparent color of the glare source contributes more towards the glare perception. A recent study has shown that the metameric sources with different SPDs but the same CCT did not lead to different glare perceptions (Huang et al., 2018). Therefore, implying that the SPD did not influence directly, but it is the CCT that determined the glare perception. However, this finding cannot be extrapolated directly to the daylit environment, and therefore, further investigations are required in this direction.
- The positional sensitivity in the perception of colored glare sources should be evaluated. Studies have reported that color perception varies across the visual field, more specifically, sensitivity to red-green opponent channel declines more steeply towards the periphery than the sensitivity to blue-yellow or black-white (luminance) channels owing to the spatial distribution of cones in the retina (Hansen et al., 2009; Mullen et al., 2005).
- Based on the results from the first three points, the effect of color on the glare model could be accounted for in possibly two different ways as also suggested by Yang et al.(Yang et al., 2016): by evaluating photoreceptors' contributions from both chromatic and achromatic channels where the weighting of each channel will depend on the subjective glare outcomes from differently colored glare sources or by evaluating the color appearance models (CAMs) and parameters associated with the CAMs such as brightness, hue, chroma, saturation calculated for the colored glare scenarios. These approaches should be compared in terms of accurately determining the discomfort glare perception.
- Lastly, a special case could be proposed to account for the variations in glare perception from the blue-colored glare sources where macular pigments were found to contribute to glare reduction (Chapter 8). However, to implement this step, we first need to evaluate the extent to which MP contributes to glare reduction in relation to the glare source spectrum and the relative position of the glare source.

To address these objectives through user studies, it is necessary to properly measure the spectral characteristics of the tested conditions. The HDR imaging method which is currently used to evaluate glare metrics and scene luminance can only measure in three color channels and therefore, limits the possibility of measuring the SPD of scene images for glare model development for colored light sources. A desirable solution would be to have hyperspectral imaging devices where the SPD of each pixel in the images can be possibly measured. However, at the time there are no such devices that can measure in the range required for glare evaluations.

A possible simulation approach would be to implement lighting simulation tools such as Alfa and Lark that allow daylight simulation in 81- and 9-channels, respectively, and can be adapted for the spectral rendering of glare conditions (Balakrishnan & J.Jakubiec, 2019; Pierson, Gkaintatzi-Masouti, et al., 2021). Such tools can provide high-resolution spectral data on colored glare sources which would be necessary to evaluate glare when considering the influence of color.

9.3 Outlook

This thesis aimed to advance the understanding of the human perception of discomfort glare from daylight and its relationship with specific environmental and physiological factors, with the ultimate goal of better integrating daylight strategies in indoor spaces. The present research work sought an evidence-based characterization of glare risks in certain visual environments with colored glare sources and an exploration of inter-individual variability in glare perception by investigating the influence of macular pigment on glare sensitivity.

As stated in the introduction, exposure to daylight can elicit a range of human responses. While discomfort glare is an undesired outcome, there are also several positive impacts of daylight on humans, including reduced stress, increased productivity, and regulation of circadian rhythm. To develop a comprehensive understanding of how daylight affects human perception and sensory processes, it is necessary to consider these responses holistically, rather than in isolation. Another aspect of holistic evaluation is considering the variability in the population. While this thesis focused on a homogenous population, it is important to extend the study to more complex and dynamic populations to promote inclusivity and better understand variabilities. Since similar daylight exposure might result in different responses due to inter-individual differences such as age, medical status, and physical and mental health, it is necessary to study this diversity.

The current era of technological advancements has enabled researchers to study visual comfort in greater depth, which can eventually lead to a better understanding of discomfort from glare. The use of advanced devices and measurement tools, such as eye-tracking devices, brain imaging, and retinal imaging technology, has created exciting opportunities for exploring connections between various aspects of visual perception, including discomfort, attention and gaze behavior, and neural activity. These breakthroughs have the potential to significantly impact the development of prediction models and ultimately the facade systems, glazing, and shading technologies that can better respond to the environment and occupants which can lead to greater comfort, satisfaction, and health benefits.

Lastly, the cross-disciplinary approach followed by this thesis yielded novel insights into the spectral sensitivity of the human eye and the role of pre-receptor filters in the glare mechanism, therefore not only advancing knowledge in the field of lighting and discomfort glare but also contributing to the field of vision psychophysics. This work highlights the importance of cross-disciplinary methods in developing holistic solutions for real-world problems. This research can hopefully inspire further multidisciplinary research to better comprehend the relationship between humans and their built environment.

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A.Appendix

A.1 Questionnaires

The four documents in the following pages are examples of the preselection, background, comfort and debriefing questionnaires were asked in three user studies.

1. Pre-selection Questionnaires

ID 5

We are looking for healthy people, not consuming any psychostimulant and any hallucinogen (e.g., cannabis, cocaine, etc.) and not having an excessive consumption of alcohol (definition as per WHO "repeated use and dependence despite recurrent adverse consequences"). Please answer the questionnaire only if you respect these criteria.

Background info

VALIDATION Must be numeric

ID 94

What is your age? *

ID 95

What is your gender? *

- Male
- Female
- I prefer not to say

VALIDATION Must be numeric

ID 96

What is your weight (in kg)? *

VALIDATION Must be numeric

ID 97

What is your height (in cm)? *

ID 98

Are you color blind? *

- Yes, red-green
- Yes, blue-yellow
- No
- I am not sure

ID 139

If you are not sure about your colour vision, please take this test here and answer the question above:
Colour vision test

ID 104

Do you wear any type of vision glasses? *

- Yes, glasses
- Yes, contact lens
- No

99

Is your sight limited by an eye disease or eye disorder, even when you wear glasses or contact lenses? (For example cataract) *

- Yes - Please specify (Required)
- No

100

From which country are you originally from? *

101

How long have you been living in Switzerland? *

- Less than 6 months
- From 6 to 12 months
- From 1 to 2 years
- From 2 to 5 years
- More than 5 years

102

In which country have you lived the most in the last 5 years? *

138
What is your native language? *

140
What is your English proficiency level? *

- Advance (C1)
- Proficient (C2)
- Native language

103
Have you been in contact with the research of the LIPID laboratory (course, seminar, experiments from Geraldine Quek, Dong Kim and Caroline Karmann)? *

- Yes (please specify to what in particular):
- No

137
Do you study/work in the sustainable building sector? *

- Yes
- No

108

Are you sensitive to the following: *

	Yes	No	I don't know
Cold	○	○	○
Heat	○	○	○
Bright light	○	○	○
Noise	○	○	○
Odour	○	○	○

Chronotype

119

In the questionnaire below, you report on your typical sleep behaviour over the past 4 weeks. We ask about work days and work-free days separately. Please respond to the questions according to your perception of a standard week that includes your usual work days and work-free days.

LOGIC Show/hide trigger exists.

120

Do you have a regular work schedule? *

○ Yes ○ No

LOGIC Hidden unless: Question "Do you have a regular work schedule?" is one of the following answers ("Yes")

ID 121

How many days do you work per week?

○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7

ID 122

Please respond to the following questions on a 24-hour time scale. *

	Workdays	Free Days
At what time do you go to bed?*		
At what time do you get ready to fall asleep?		
How many minutes do you need to fall asleep?		
At what time do you wake up?		
How many minutes it take for you to get up?		

ID 130

*Note that some people stay awake for some time when in bed!

131

Do you use an alarm clock to wake up? *

	Yes	No
Workdays	○	○
Free days	○	○

LOGIC Hidden unless: (Question "Workdays" is one of the following answers ("Yes") OR Question "Free days" is one of the following answers ("Yes"))

134

Do you regularly wake up BEFORE the alarm rings? *

○ Yes ○ No

LOGIC Show/hide trigger exists.

135

Are there any particular reasons why you **cannot** freely choose your sleep times on free days? *

○ Yes ○ No

LOGIC Hidden unless: Question "Are there any particular reasons why you **cannot** freely choose your sleep times on free days? " is one of the following answers ("Yes")

ID 136

What are the reasons? *

- ☐ Child(ren)/pet(s)
- ☐ Hobbies
- ☐ Other - Write In (Required) ______ *

Contact details

ID 85

Please provide the following information: *

First name ______

Email address ______

Mobile phone (+41 ...) ______

(untitled)

ID 116

By filling this form, I provide my consent to use this information for checking my eligibility condition for the study. I understand that my personal information given in this survey will only be used by the researcher if I am eligible for this study and further participate in the study. Otherwise, this information will be removed from the survey data.

117

Please indicate that you have read the above information and agree to it. *

☐ I have read the information and I agree to it.

Thank You!

1

Thank you for proposing your candidature to the experiment!

You will be contacted as soon as possible to confirm or not your participation in the study.

2. Background Questionnaires

Background questionnaires updated

126
1. Participant's code: *

Visual acuity test

150

Please click on the link below and run the application:
Visual acuity test

While doing the test, please maintain your normal posture and do not move closer to the screen.
Ask the researcher in case of any questions.

151
2. Have you done the Visual acuity test above? *

Yes No

Contrast test

141

Please click on the link below and run the application:
Contrast test

While doing the test, please maintain your normal posture and do not move closer to the screen.
Ask the researcher in case of any questions.

142

3. Have you done the contrast test above? *

○ Yes ○ No

Colour blindness test

155

Please click on the link below to run the test:
Colour blindness test

Your details

159

4. Please write your full name:

160
5. Please write your email address:

(untitled)

10
6. Are you left or right handed? *

- Left
- Right
- Both

120
7. Gender: *

- Female
- Male
- Prefer not to say

VALIDATION Must be numeric
121
8. Age: *

ID 11

9. What color are your eyes? *

- Blue/green/grey
- Brown/Hazel
- Black
- Other - Write In (Required)

LOGIC Show/hide trigger exists.

ID 93

10. Are you in healthy conditions right now? *

- Yes
- No

LOGIC Hidden unless: #10 Question "Are you in healthy conditions right now?" is one of the following answers ("No")

ID 125

11. Please call the researchers and discuss with them about your conditions. *

LOGIC Show/hide trigger exists.

ID 105

12. Are you wearing glasses or contact lenses? *

- Yes, glasses
- Yes, contact lenses
- No

LOGIC Hidden unless: #12 Question "Are you wearing glasses or contact lenses?" is one of the following answers ("Yes, glasses","Yes, contact lenses")

ID 146

13. The reason why you wear glasses or contact lenses is because you have...(Multiple response possible) *

- ☐ Myopia (I see distant objects badly)
- ☐ Hyperopia (I see nearby objects badly)
- ☐ Astigmatism (I see objects with deformation)
- ☐ Other - Write In (Required)

*

(untitled)

ID 106

14. Please indicate how you feel at this moment. For each pair, put your vote closer to the adjective which you believe to describe your feelings better: *

	1	2	3	4	5	6	7	
Unhappy	○	○	○	○	○	○	○	**Happy**

ID 115

A *

	1	2	3	4	5	6	7	
Annoyed	○	○	○	○	○	○	○	**Pleased**

116
A *

	1	2	3	4	5	6	7	
Unsatisfied	○	○	○	○	○	○	○	**Satisfied**

117
A *

	1	2	3	4	5	6	7	
Sleepy	○	○	○	○	○	○	○	**Wide awake**

118
A *

	1	2	3	4	5	6	7	
Agitated	○	○	○	○	○	○	○	**Relaxed**

119
A *

	1	2	3	4	5	6	7	
Not alert	○	○	○	○	○	○	○	**Alert**

143
15. Does your usual workday consist of predominantly screen-based tasks?*

○ Yes ○ No

LOGIC Show/hide trigger exists.

ID 144

16. Have you had coffee, tea, or an energy drink since you got up?*

- No
- Yes

LOGIC Hidden unless: #16 Question "Have you had coffee, tea, or an energy drink since you got up?" is one of the following answers ("Yes")

ID 145

17. How many cups did you have?*

- 1
- 2
- More than 2

ID 149

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

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

(untitled)

ID 122

19. Is the view to the outside important for you, in general?*

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	**Very much**

158

20. Which of these best describe where you live currently?*

- City centre
- City suburbs
- Town centre
- Town suburbs
- Large village (population more than 2,000)
- Small village (population less than 2,000)
- Hamlet (population less than 100)
- Isolated house or farm

94

21. Please assign a rating for your sensitivity to the following items:*

	Not sensitive	Slightly sensitive	Sensitive	Very sensitive	I don't know
Dry air	○	○	○	○	○
Draft*	○	○	○	○	○
Noise*	○	○	○	○	○
Odour	○	○	○	○	○
Humid air	○	○	○	○	○
Heat	○	○	○	○	○
Stuffy air	○	○	○	○	○
Cold	○	○	○	○	○

ID 140

*help:
Draft: refers to a current of air being drawn indoors
Noise: refers to unwanted sound

LOGIC Show/hide trigger exists.

ID 130

22. Are you sensitive to bright light in general? *

Yes	No	I don't know
○	○	○

LOGIC Hidden unless: #22 Question "Are you sensitive to bright light in general?" is one of the following answers ("Yes","No")

ID 129

23. Please rate your sensitivity to bright light: *

	0	1	2	3	4	5	6	7	8	9	10	
Not sensitive	○	○	○	○	○	○	○	○	○	○	○	**Very sensitive**

ID 139

24. Are you experiencing any eye fatigue or pain on your eyes? *

None	Slight	Moderate	Severe
○	○	○	○

157
25. How would you rate the overall indoor environment comfort? *

Very uncomfortable	Uncomfortable	Comfortable	Very comfortable
○	○	○	○

123
26. Is there anything about the physical environment that disturbs you in this moment? *

(untitled)

147

Please click on the link below and run the application:
Contrast test

While doing the test, please maintain your normal posture and do not move closer to the screen.
Ask the researcher in case of any questions.

148
27. Have you done the contrast test above? *

○ Yes ○ No

Thank You!

3. Comfort Questionnaires

User ID

125
Participant's code: *

191
Survey
number

Contrast test

260

Please click on the link below and run the application:
Contrast test

While doing the test, please maintain your normal posture and do not move closer to the screen.
Ask the researcher in case of any questions.

ID 170

Is there anything about the physical environment that disturbs you at this moment? *(Answer "No", if your physical environment is not disturbing) *

Your physical environment

LOGIC Show/hide trigger exists.

ID 153

How would you rate the overall indoor environment? *

Very uncomfortable	Uncomfortable	Comfortable	Very comfortable
○	○	○	○

LOGIC Hidden unless: Question "How would you rate the overall indoor environment?" is one of the following answers ("Comfortable","Very comfortable")

ID 261

Is there any specific reason why you find the overall indoor environment comfortable? *

LOGIC Hidden unless: Question "How would you rate the overall indoor environment?" is one of the following answers ("Very uncomfortable","Uncomfortable")

ID 262

Is there any specific reason why you find the overall indoor environment uncomfortable? *

ID 105

At this precise moment, how are you feeling? *

Cold	Cool	Slightly cool	Neither cool or warm	Slightly warm	Warm	Hot
○	○	○	○	○	○	○

ID 263

How satisfied are you with the thermal situation in this room? *

Very dissatisfied	Dissatisfied	Neither dissatisfied nor satisfied	Satisfied	Very satisfied
○	○	○	○	○

ID 264

How satisfied are you with the air quality in this room? *

Very dissatisfied	Dissatisfied	Neither dissatisfied nor satisfied	Satisfied	Very satisfied
○	○	○	○	○

265

How satisfied are you with the acoustics in this room? *

Very dissatisfied	Dissatisfied	Neither dissatisfied nor satisfied	Satisfied	Very satisfied
○	○	○	○	○

270

To what extend do you agree or disagree with the following statements? *

	1-Strongly disagree	2	3	4	5	6	7-Strongly agree
My skin color looks natural	○	○	○	○	○	○	○
The colors of the objects inside the room look natural	○	○	○	○	○	○	○
I can see the surrounding buildings	○	○	○	○	○	○	○
I can distinguish the color of the moving cars on the street	○	○	○	○	○	○	○
I can tell the sky conditions outside (e.g., sky color, presence of clouds)	○	○	○	○	○	○	○
By looking outside the window, the environment and the elements look natural	○	○	○	○	○	○	○
The colors of the sky and trees look natural	○	○	○	○	○	○	○

Comments

249
How do you find the current visual environment? *

Very uncomfortable	Uncomfortable	Comfortable	Very comfortable
○	○	○	○

250
How satisfied are you with the overall lighting quality in this space? *

Very dissatisfied	Dissatisfied	Neither satisfied nor dissatisfied	Satisfied	Very satisfied
○	○	○	○	○

251
How do you perceive the light level on your desk in this moment? *

Very low	Low	Slightly low	Just right	Slightly high	High	Very high
○	○	○	○	○	○	○

243
To what extent do you agree/disagree with the following statements:

	Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
I am comfortable with the brightness and the contrast of the light in my field of view	○	○	○	○	○

282

How do you find the present light color in this room? *

Very comfortable	Comfortable	Uncomfortable	Very uncomfortable
○	○	○	○

287

Please indicate how you perceive the lighting in the room in this moment. For each pair, put a check mark closer to the adjective which you believe to describe the light better.

	1	2	3	4	5	6	
Warm	○	○	○	○	○	○	**Cold**

289

—

	1	2	3	4	5	6	
Relaxing	○	○	○	○	○	○	**Stimulating**

291

—

	1	2	3	4	5	6	
Unpleasant	○	○	○	○	○	○	**Pleasant**

241

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

Imperceptible	Noticeable	Disturbing	Intolerable
○	○	○	○

242

Definition: Glare is the sensation of visual discomfort caused by differences between light and dark areas, or by excessive brightness in your field of view.

239

Are you experiencing any discomfort due to glare at the moment? *

Yes	No
○	○

240

Definition: Glare is the sensation of visual discomfort caused by differences between light and dark areas, or by excessive brightness in your field of view.

237

How much discomfort due to glare are you experiencing at the moment? *

Not at all	Slightly	Moderately	Vey much
○	○	○	○

238

Definition: Glare is the sensation of visual discomfort caused by differences between light and dark areas, or by excessive brightness in your field of view.

235

On a scale of 0-10, how much discomfort due to glare are you experiencing at the moment? *

	0	1	2	3	4	5	6	7	8	9	10	
Not at all	○	○	○	○	○	○	○	○	○	○	○	**Very much**

236

Definition: Glare is the sensation of visual discomfort caused by differences between light and dark areas, or by excessive brightness in your field of view.

233

How acceptable is the glare you are experiencing at the moment, if any? *

Unacceptable	Just unacceptable	Just acceptable	Acceptable
○	○	○	○

234

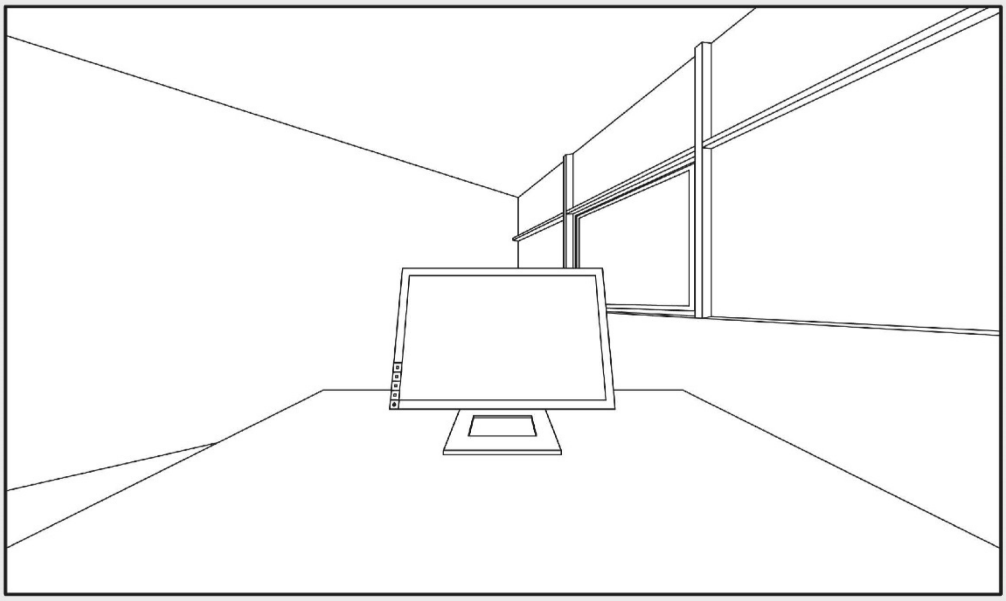
Definition: Glare is the sensation of visual discomfort caused by differences between light and dark areas, or by excessive brightness in your field of view.

267

For this question, please ask the researcher-in-charge for assistance.

If you experience any uncomfortable glare at the moment, please color the cause(s) or source(s) of glare on the diagram on the paper.
If not, leave it blank.

268



Eye strain

224

Are you experiencing any eye fatigue or pain on your eyes?

None	Slight	Moderate	Severe
○	○	○	○

Glazing change

LOGIC Show/hide trigger exists.

ID 285

Assume you have to conduct your daily work in this space, would you change the current glazing configuration?
*

- ○ I have no preference
- ○ No, I am comfortable and do not require any change of the window or shading device
- ○ No, even though I am slightly uncomfortable
- ○ Yes, I would like to change

LOGIC Hidden unless: Question "Assume you have to conduct your daily work in this space, would you change the current glazing configuration?
" is one of the following answers ("Yes, I would like to change")

ID 286

How would you change it? *

- ☐ Make the glazing more uniform
- ☐ Add a textile shading
- ☐ Add venetian blinds
- ☐ Other - Write In (Required)

*

LOGIC Show/hide trigger exists.

ID 283

Did you wear eye-tracking glasses during the past 10 minutes?

*

- [ ] Yes
- [ ] No

LOGIC Hidden unless: Question "Did you wear eye-tracking glasses during the past 10 minutes?
" is one of the following answers ("Yes")

ID 284

How much did the eye-tracking glasses disturb your normal visual conditions?

*

1-Not at all	2	3	4	5	6	7-Very much
○	○	○	○	○	○	○

Thank You!

ID 1

Thank you for your answers! Please contact the researcher for further instructions.

4. Debriefing Questionnaires

Debriefing questionnaire col2

161
1. Participant's code: *

(untitled)

165
2. During your stay in this room, have you been uncomfortable with any of the following indoor conditions?

	Very Uncomfortable	Uncomfortable	Comfortable	Very Comfortable
Noise				
Cold				
Heat				
Odour				

134
3. How satisfied are you with the view to the outside? *

Very dissatisfied	Dissatisfied	Neither satisfied nor dissatisfied	Satisfied	Very satisfied

170
4. How clear is your view to the outside?

	0	1	2	3	4	5	6	7	8	9	10	
Not clear at all												**Very clear**

171

5. Rate the importance of the following elements in your appraisal of a view (in general):*

	1 - Not important	2	3	4	5	6	7 - Very important
The view of other constructions (buildings)	○	○	○	○	○	○	○
The view is dynamic (i.e., presence of movement outside)	○	○	○	○	○	○	○
The view offers me a sense of spaciousness	○	○	○	○	○	○	○
The diversity seen within the view (mixture of trees, buildings, etc.)	○	○	○	○	○	○	○
The view of natural elements (trees, birds)	○	○	○	○	○	○	○
The view of the sky	○	○	○	○	○	○	○
The colour of the various elements seen within the view	○	○	○	○	○	○	○
The proximity of outdoor elements (i.e., position of the trees)	○	○	○	○	○	○	○

192

6. Do you think that the view to the outside is restricted by the current glazing?*

	1	2	3	4	5	6	7	
Very much restricted	○	○	○	○	○	○	○	**Not at all restricted**

180

7. Please take a look at the view outside and rate the following: *

	1 - Strongly agree	2	3	4	5	6	7 - Strongly disagree
The view outside looks interesting	○	○	○	○	○	○	○
The view outside looks beautiful	○	○	○	○	○	○	○
The view outside looks calming (i.e., could make me feel relax)	○	○	○	○	○	○	○
The view outside looks busy	○	○	○	○	○	○	○
The outdoor environment looks safe	○	○	○	○	○	○	○
The view outside looks stimulating (i.e., engaging)	○	○	○	○	○	○	○
The view outside looks pleasant (i.e., could make me feel happy)	○	○	○	○	○	○	○
The view outside looks spacious (i.e., open)	○	○	○	○	○	○	○
The view outside looks monotonous (i.e., boring)	○	○	○	○	○	○	○
I would frequently look at this view if it was my workstation (i.e., when taking a break)	○	○	○	○	○	○	○
The view outside might distract me from working	○	○	○	○	○	○	○

LOGIC Show/hide trigger exists.

195

Out of the test conditions shown to you, Which conditions do you prefer the most?

(more than one selection is possible) *

- ☐ Red glazing
- ☐ Blue glazing
- ☐ Green glazing
- ☐ Neutral (grey) glazing
- ☐ None of the above

LOGIC Hidden unless: Question "Out of the test conditions shown to you, Which conditions do you prefer the most?

(more than one selection is possible)"

ID 194

Why did you choose the above option? *

Rate glazing

ID 196

8. Please rate the four glazing that you experienced in terms of most visually comfortable to least visually comfortable in controlling glare from the sun:

Drag items from the left-hand list into the right-hand list to order them.

- Blue glazing
- Neutral (grey) glazing
- Red glazing
- Green glazing

(untitled)

ID 160

9. Do you have any remark regarding the experiment? Any feedback is welcome!*

Thank You!

ID 1

Thank you for your answers and your participation to the experiment!

A.2 Additional publications

At different stages during the doctoral research, three peer-reviewed conference papers written by a first author were published based on the three user studies conducted under the scope of this doctoral thesis. Additionally, one peer-reviewed conference article co-written as a second co-author was published and one journal article where contributions were made as a second author is under review.

Papers published in peer-reviewed conferences as a first author are:

1. **S Jain,** C Karmann, J Wienold, Subjective assessment of visual comfort in a daylit workplace with an electrochromic glazed façade, Journal of Physics: Conference Series, 2021.
2. **S Jain**, J Wienold, M Andersen, Comparison between CIE 2° and 10° field photopic luminosity functions V(λ) for calculating daylight discomfort glare metrics, Lux Europa 2022, Prague, Czech Republic.
3. **S Jain**, J Wienold, M Andersen, Effect of window glazing color and transmittance on human visual comfort, PLEA 2022, Santiago, Chile.

Papers published in a peer-reviewed conference as a second author are:

4. J Wienold, **S Jain,** M Andersen, Transmittance thresholds of electrochromic glazing to achieve annual low-glare work environments, Nordic IBPSA 2022, Copenhagen, Denmark.

Papers *under review* in a journal as a second author is:

5. G Quek, **S Jain**, C Karmann, C Pierson, J Wienold, M Andersen, A critical analysis of questionnaire items for discomfort glare studies in daylit spaces, *Lighting Research & Technology* (Under Review)

Subjective assessment of visual comfort in a daylit workplace with an electrochromic glazed façade

S Jain[1], C Karmann[1] and J Wienold[1]

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

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Abstract. Electrochromic (EC) glazing is increasingly employed in building façades to achieve better visual comfort for the occupants. EC glazing can modulate the light entering through the façade by varying the solar transmittance of the glass and therefore can work as a shading strategy to minimize solar heat gains or glare. However, it also alters the spectrum and distribution of light entering through the façade, which influences certain visual attributes associated with a space. This user assessment study evaluates some of these attributes including the colour perception of the elements inside and outside the room, the uniformity of daylight distribution, the clarity of the view through the glazing and the perception of glare when the sun is in the field of view. Results indicate a visual transmittance (τ_v) of 0.6% is sufficient to control glare when the sun is in the peripheral field of view (FOV) while $\tau_{v,n\text{-}n}$ of 0.14% is required to control glare when the sun is close to the central FOV. Most of the participants did not perceive the colours of outdoor environment as natural when seen through EC glazed window. The majority of participants also desired to change the glazing configuration by adding an additional shading device.

1. Introduction

The highly variable nature of daylight often leads to either too little or too much light which can cause visual discomfort. A key to better daylight utilization and therefore, better visual comfort is the ability to modulate the daylight. EC glazing with its variable visual transmittance (τ_v) technology offers control over the visual and thermal environment [1] and can help mitigate the discomfort glare from daylight while maintaining a clear view to the outside [2]. Most of the currently available EC technologies also show a shift in the spectral transmission in the darkened state, causing it to appear blue in color. On the other hand, the spectral composition of the light is known to influence visual quality and user acceptance of a space [3]. Previous visual comfort research on EC glazing based on simulation [4], physical measurements [2], [5] and human participants [6], [7] indicate its capability in reducing glare. However, there is no clear indication of the maximum acceptable transmittance of EC glazing required to minimize glare with the sun in the field of view (FOV). There are also very few studies on visual quality aspects such as color perception and view out through EC glazing [8].

This study evaluates various perceived visual comfort aspects of the application of EC glazing in a facade including discomfort glare, view out, color perception of the elements inside and outside the room. We conducted test room experiments with 20 participants and exposed them to four visual scenarios that vary in the sun-disk luminance and in the viewing direction towards the sun to determine the τ_v required to control glare in critical and non-critical viewing directions. For each visual scenario, we also evaluated the acceptance of the glazing configuration, color perception of the view out and the elements inside the room created by such visual transmittance of the glazing.

2. Method

2.1. Experimental design and set-up

Experiments were conducted with 20 healthy participants aged between 19 and 30 years in an office-like test room at EPFL campus in Lausanne, Switzerland during winter 2019-20 on clear sky sunny days. The experiments were approved by the EPFL Human Research Ethics Committee (No. 065-2019). Each participant was exposed to four scenarios, varying in luminance of the sun disk, and viewing direction with respect to the sun. Daylight was the only source of light during the exposure to four visual scenarios and the experimental setup chosen in a way that the only glare source experienced by the subjects was the sun seen through an EC switched glazing unit. The test room had a south facing window façade (window-to-wall ratio = 62%) consisting of 6 panes of EC glass, each of which could be individually controlled to vary the transmittance. The participant's desk was equipped with illuminance sensors measuring continuously horizontal and vertical illuminance (Figure *1*(b)). A luminance camera (*LMK 98-4 color HighRes)* with a fish-eye lens and a neutral density filter ND3 was used to capture the High Dynamic Range (HDR) images of each visual scene at participant's eye position before and after their exposure to the scene. A handheld illuminance sensor was mounted just below the lens of the luminance camera to record the vertical illuminance value for each captured image. A 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. An indoor comfort sensor (*Testo 480)* was used to continuously record the air and globe temperature, air velocity, relative humidity, and $CO2$ content in test room.

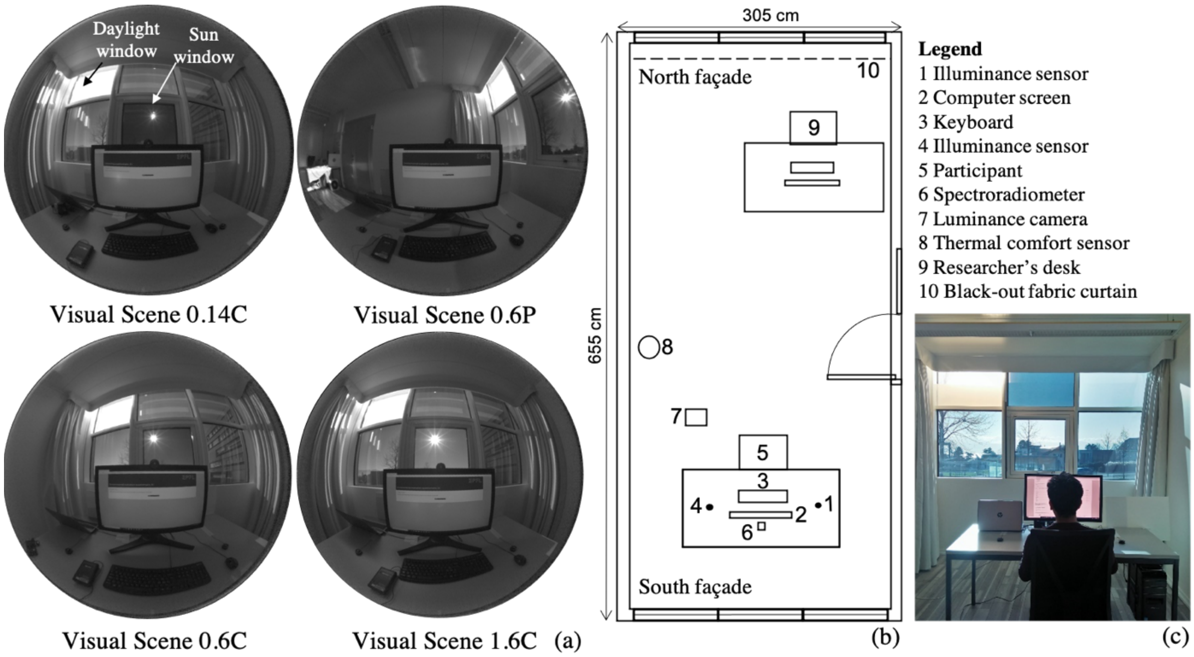

Figure 1(a) Fisheye HDR images of four visual scenarios shown to the participants, (b) test room layout showing all the equipment and (c) Participant performing the task in the test room

Participants were exposed to four visual scenarios with the sun always in their FOV (Figure *1* (a) and (c)). To create the four scenarios, we altered the τ_v of EC windowpane through which the sun was visible to the test person (named as "sun window") and we changed the subjects' viewing direction by rotating their desk to have the sun (glare source) close to their central FOV (critical viewing direction, angle between viewing direction and sun were in the range of 13°-36°, the average angle was 27°), labelled "C", and peripheral FOV (non-critical viewing direction, angle between fovea and sun were in the range of 40°-83°, the average angle was 58°), labelled "P". For two of the six EC glazing units the spectral transmittance was measured for the used switching states at the LESO lab.
Following this, we defined the naming convention of the four scenarios of the article as:

i. "1.6C": τ_v of the sun window of 1.6% and sun in the participants' central FOV

ii. ”0.6C”: τ_v of the sun window of 0.6% and sun in the participants’ central FOV
iii. ”0.6P”: τ_v of the sun window of 0.6% and sun in the participants’ peripheral FOV
iv. ”0.14C”: τ_v of the sun window of 0.14% (achieved by installing a removable colour neutral window filter of 22% τ_v over the EC glazing 0.6%) and sun in the participants’ central FOV

2.2. Experimental procedure
The testing sessions were conducted on clear sky sunny days between 8:30 to 13:30, lasting for two hours each with one participant at a time. After getting introduced to the protocol, participants answered background questions about their demographics and indoor environmental preferences. Participants were then exposed to four identical scenarios in randomized order, each preceded by a break (~12 minutes). During the break, participants wore an eye mask and headphones to listen to music and relax, while the researcher took measurements and HDR images before and after each exposure, prepared the room for next scenario by changing glazing transmittance and rotating the participant’s desk. During the exposure to each scenario, (~12 minutes), the participants were first asked to perform a simple typing task (allowing them to adapt to the visual environment) and then to report their perception of each condition in a questionnaire. Participants evaluated the discomfort glare, lighting levels, and colour perception associated with each condition. At the end of the experiment, they answered additional debriefing questions pertaining to the view to the outside through the glazing.

2.3. Subjective questionnaires
Survey questionnaires were answered on binary, categorial (Likert) or ordinal scales. 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. Questions about the glare, glazing configuration and colour perception were asked in every scenario while questions on view out were asked once at the end of the experiment. We analyse responses pertaining to discomfort glare, colour perception, view out and glazing configuration in the subsequent section.

3. Results and discussion

3.1. Discomfort Glare
We calculated daylight glare probability (DGP) [9] values of the scenarios from the respective HDR images using Evalglare [10] in Radiance [11]. Mean DGP values of the four visual scenarios as shown in Figure *2* (b) directly relate to the glazing transmittance with “0.14C” being the lowest and “1.6C” being the highest and the viewing direction “0.6P” lower than “0.6C” due the sun position in peripheral FOV. Subjective responses to glare as shown in Figure *2* (a) show a similar trend as the mean DGP values. The scenes 0.14C and 0.6P are rated as not causing discomfort due to glare by majority of participants, while votes in scene 1.6C indicate the inability of the tested EC glazing to minimize glare at 1.6% τ_v in a critical viewing direction. In scene 0.6C, 53% of the participants reported discomfort due to glare which was the lowest τ_v achieved by the tested EC glazing, indicating the need of lowering the transmittance further in cases when the sun is close to the viewing direction.

3.2. On the need to change the tested glazing configuration
The tested glazing configuration as shown in Figure *1* had one windowpane of low τ_v values (0.14%, 0.6% and 1.6%) during four scenarios, another one windowpane at maximum τ_v of 56% to allow sufficient daylight and the remaining four panes were set to 4%. Figure *3*(a) presents the distribution votes on the requirement to change the glazing configuration in each visual scenario. It can be inferred that a lower number of participants expressed a need to change the glazing configuration for lower EC transmittance (15% for scene 0.14C compared to 50% for scene 1.6C compared) suggesting that discomfort glare from the sun through the glazing to be a driver for requesting a change. However, for the visual scenario 0.6P although glare was not discomforting for most of the participants (Figure *2*(a)),

there are still a higher number of votes for the desire to change the glazing configuration. The cases of participants not wanting to change the glazing, even though they were uncomfortable, highlights the greater tolerance towards acceptance compared to discomfort. Such scenarios can be explored in the glazing control protocol to allow a trade-off between comfort and energy saving decisions. Further examining the votes in the branching question (Figure *3*(b)), a majority of the participants desired to have an additional shading system, while some also wanted to have the glazing more uniform since the configuration used in the experiment was not uniform.

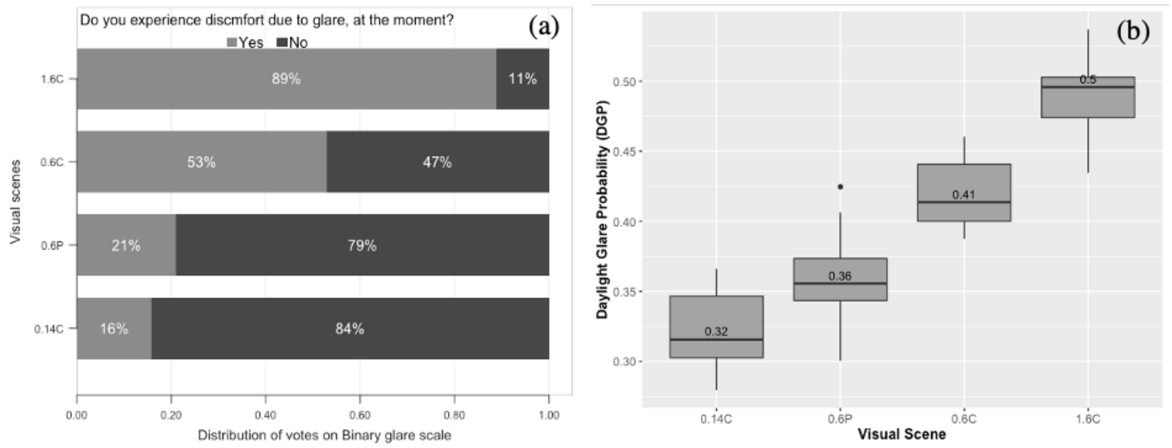

Figure 2 (a) Distribution of subjective glare votes on binary glare scale for each visual scenario, (b) DGP boxplots with mean values for each visual scenario

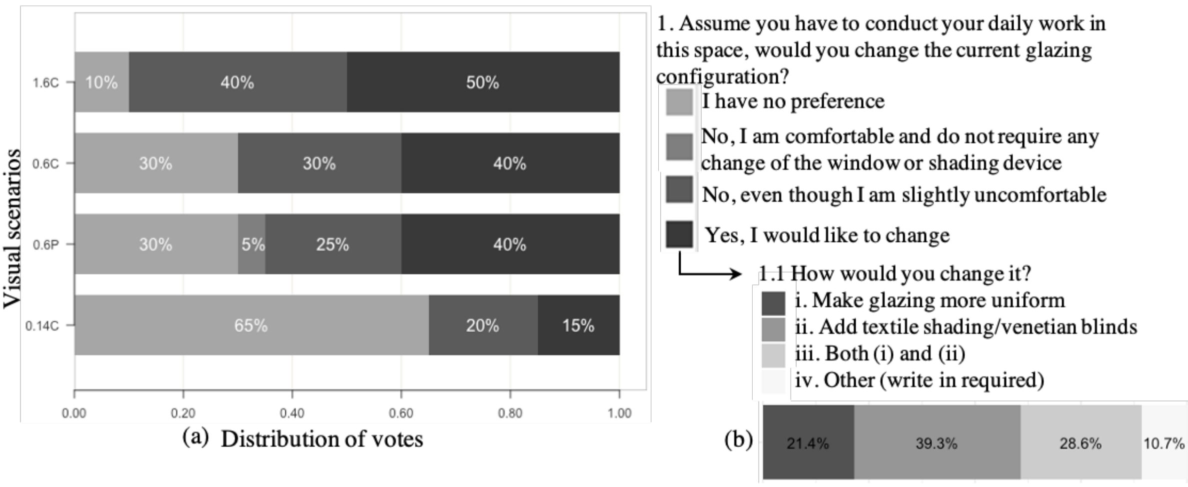

Figure 3 (a) Responses for requirement to change the glazing configuration in four visual scenario (b) Responses for branching question (Note: in option (ii) we combined the two separate options: "Add textile glazing" and "Add venetian blinds")

3.3. View out perception

An average of 37% votes found the outside view to be restricted by the EC glazing, which is less than the reaction to view restriction by venetian blinds observed in a study by J. Wienold [12] where 74% of participants found the view to the outside was restricted by venetian blinds, 53% by specular blinds and 68% by a vertical foil system. However, it is still surprising to have 37% responses finding the view restricted given that EC technology maintains a clear view to the outside.

3.4. Colour perception

Figure 4 demonstrates the measured chromaticity coordinates and the correlated colour temperature (CCT) corresponding to four visual scenarios. We can see in Figure 4 (a) the experimental conditions are very close to each other in terms of quality of colour, thereby validating our approach to keep the colours similar between the scenarios. In Figure 4 (b), CCT values calculated from the integral arriving at the sensor are driven more by the sun intensity as scene 1.6C shifts more towards the blue than 0.14C, even though the blue tint is stronger in Scene 0.14C. Therefore, the measurements may not represent participants' colour perception of inside elements, and this can be confirmed with subjective votes shown in Figure *5* where a majority of participants perceived inside colours as natural.

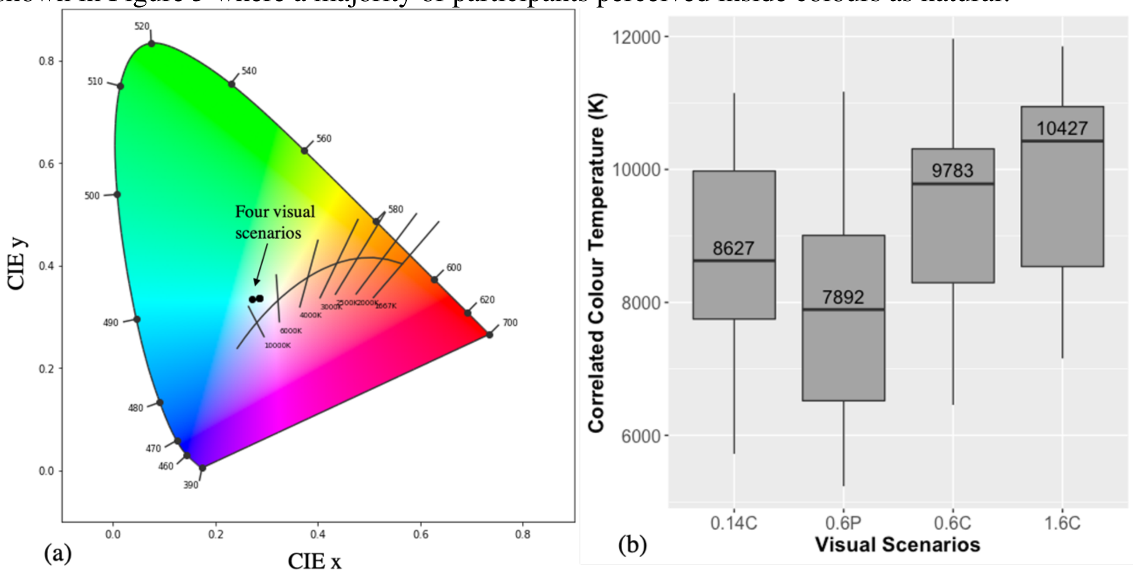

Figure 4 (a) Chromaticity coordinates (x, y) of four visual scenarios (median values) with the blackbody locus, (b) CCT of four visual scenarios presented in boxplots with median values

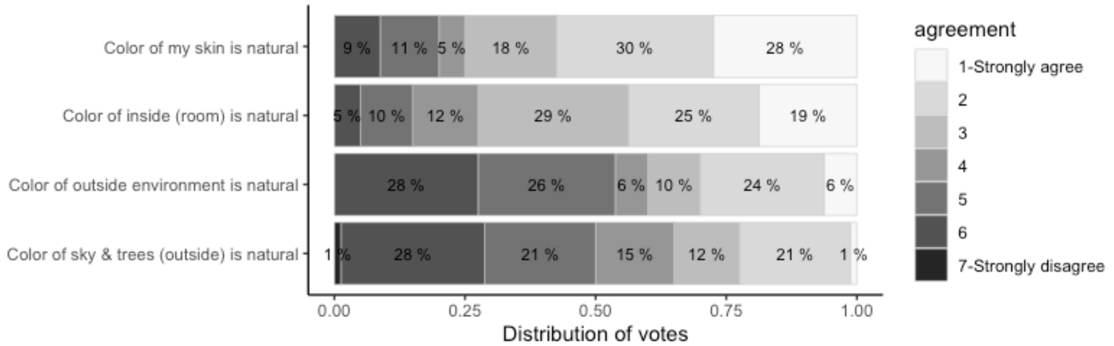

Figure 5 Votes on colour perception of the objects inside and outside the test room

Figure 5 shows the distribution of votes on naturalness of colours of the objects inside and outside the test room as perceived by the participants for all the test cases. The colours inside the room are rated as natural compared to the outside colours because of the control strategy used in our protocol to keep one windowpane in clear state for maintaining the natural colour of elements inside the room. However, the colours of the outdoor environment were perceived as non-natural in 54% of the cases due to the blue tint created by the glazing at low transmittance levels. These results also agree with literature [8]. We performed a statistical analysis to test the influence of the different scenarios on these results but did not observe significant differences. However, when comparing the participants who explicitly indicated colour as an important element in appraisal of view out (50% of the sample) from the rest of the sample, we found both statistical and practical significant differences (Wilcoxon test $p<0.05$ with small or medium effect size) in colour perception between the two groups. This difference was stronger for the colour of the outside environment ($p<0.001$, $\varrho_{Spearman}=0.45$). We conclude that there is a noticeable personal difference in colour perception, with 50% of people strongly noticing the colour change brought about by the EC glazing.

4. Conclusions

In this study, we evaluated the visual comfort and quality aspects of a workplace scenario equipped with an EC glazed façade as experienced by the participants. Results demonstrate the minimum τ_v ~0.6% achieved by blue-tinted EC glazing is adequate to control discomfort glare when the sun is in the peripheral FOV, however, the same is not applicable when the sun is in the central FOV. This can be explained by the directional sensitivity of the retina [13] and also highlights the importance of considering physiological parameters in designing spaces. A τ_v of 0.14% was found to be suitable in minimizing glare for a critical viewing direction. Most of the participants desired to change the glazing configuration by adding an additional shading device, except in Scene 0.14C. Results also showed that even in an uncomfortable glare scenario (Scene 1.6C) 40% of the participants did not want to change the glazing configuration indicating a higher acceptance threshold. This outcome can be used for advanced control algorithms to optimize the trade-off between comfort and energy savings. Another finding of this study is that the colours of the outdoor environments rendered by the EC glazing were not perceived as natural by a majority of the participants which underlines the importance of achieving colour-neutralness for EC technology improvements. These results demonstrate the occupants' perception in such façade systems to achieve visually comfortable and pleasant spaces, to take informed decisions on façade design, glazing control system and future development goals.

5. Acknowledgement

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Comparison between CIE 2° and 10° field photopic luminosity functions V(λ) for calculating daylight discomfort glare metrics

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***Abstract*— The spectral sensitivity of the average human eye in photopic conditions is represented by the photopic luminosity function V (λ). The CIE has established the photopic luminosity functions for the 2° and 10° visual fields for a standard observer applicable for foveal and para-foveal light sources, respectively. These functions differ in short wavelength region where $V_{10°}$(λ) has higher sensitivity. However, $V_{10°}$(λ) function is not implemented in any of the discomfort glare metrics even though, for most glare scenarios, the glare source is located further than 2° from the fovea. This can result in an underestimation of the short wavelength contribution of the glare sources' spectra, and, a fortiori, in the blue-colored light sources. In this paper, we aim to determine the impact of replacing $V_{2°}$(λ) with $V_{10°}$(λ) in the daylight discomfort glare metrics for scenarios where the visible sun disk lies very much outside the 2° zone and acts as a glare source through blue-tinted and color-neutral tinted low transmittance glazing. We compare three types of colored glazed façade: color-neutral glazing, blue-tinted electrochromic (EC) glazing and an extreme case of saturated blue-tinted glazing. We found that the difference in derived glare source luminance and discomfort glare metrics is statistically significant only for the saturated blue glazing with an average 70% increase in luminance and 20% increase in DGP (i.e. one category higher discomfort) and 9% increase in CGI, when using $V_{10°}$(λ). We conclude that the impact of replacing $V_{2°}$(λ) with $V_{10°}$(λ) is negligible for standard EC or color-neutral glazing types in commercial buildings. However, specific cases of saturated blue light sources that peaks at 450nm are more accurately quantified by $V_{10°}$(λ), that produces higher values of glare metrics.**

Keywords—Discomfort glare, Spectral sensitivity, Glazing color, photopic luminosity function, Daylight

I. Introduction

Photopic luminous efficiency function *V*(λ) is the spectral weighting function that defines the average spectral sensitivity of the human visual perception of brightness [1]. The photopic human vision state applies to the scenarios having luminance higher than 5cd/m^2 that typically includes discomfort glare scenarios under daylight. Photopic luminosity function is derived experimentally based on user studies of side-by-side matching task or alternate matching (flicker photometry) [2], [3]. A relative subjective brightness perception of the lights at different wavelengths in visible spectrum is determined under constant and neutral adaptation. *V*(λ) was proposed by CIE in 1923 for a 2 degree visual field, which continues to be used in practice for most of the photometric measurement tasks and other practical lighting applications [2].

It was first investigated by Stiles and Burch in 1958 and later proved by several studies that the spectral sensitivity of human eye changes from the center towards the periphery of the retina [4]. Between the foveal and parafoveal fields, the difference in sensitivity to light is attributed to the presence of blue-light absorbing macular pigments in the foveal region of the macula [5]. The yellow macular pigments in the eye are located in front of photoreceptors and are concentrated within 3 degrees of fovea and declines in parafovea, therefore, not effecting the 10 degree field sources [6]. The absorption spectrum of macula lies between 400nm to 550nm and peaking around 460nm [7]. Following these results, CIE established photopic spectral sensitivity function CIE $V_{10°}$(λ) for parafoveal light sources up to 10 degree visual field [8]. Studies have indicated that the ratio $V_{2°}$(λ) / $V_{10°}$(λ) results in a function which is characteristic of the absorption spectrum by the macula [9].

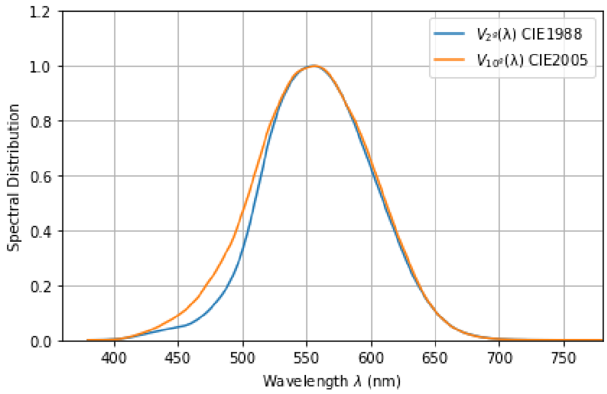

Figure 1 Comparison of 2 and 10-degree photopic luminous efficiency functions

Fig. 1 shows the 2 degree and 10-degree functions. It can be observed from Figure 1 that the difference between $V_{2°}$(λ) and $V_{10°}$ (λ) functions becomes significant between the wavelengths 450nm to 500nm where $V_{10°}$ (λ) has increased sensitivity compared to $V_{2°}$ (λ). It can be inferred that the replacing one function with the other have higher impact in case of blue light sources emitting higher quantity in short wavelength region. Previous studies have emphasized on the

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use of $V_{10°}(\lambda)$ instead of $V_{2°}(\lambda)$ for the measurement of luminance for large field sources under both photopic and mesopic adaptations [9]–[11]. Furthermore, there are ongoing discussions in the lighting community to replace $V_{2°}(\lambda)$ with $V_{10°}(\lambda)$ for extending the applicability to parafoveal sources in discomfort glare scenarios where often the glare source lies outside the fovea. However, $V_{10°}(\lambda)$ is not implemented in any discomfort glare metrics and there are no studies investigating the impact of using $V_{10°}(\lambda)$ instead of $V_{2°}(\lambda)$ for the calculation of luminance and illuminance in discomfort glare metrics for blue and non-blue light sources.

To fill this gap, this study aims to compare what difference the use of either of these two luminosity functions makes when glare metrics are applied under daylit conditions. We calculate glare from the sun visible behind three different colored glazings that have blue, saturated deep blue and color-neutral tints using $V_{2°}(\lambda)$ with $V_{10°}(\lambda)$ and compare the results within each glazing color.

II. METHOD

A. Test setup

The setup is done in a lab facility located in Lausanne, Switzerland (46°31'00.4"N 6°33'47.1"E) that is arranged to resemble an office space (Fig. 2). The test room has a south façade which provides an unobstructed view to the sun at low altitudes in winter months (mid-October to mid-March) until late afternoon. The south façade is the test façade which we manipulate to create a glare source (sun) of different spectral power distribution by installing colored glazings. The sun is the only glare source visible through the glazing in parafoveal field of view of the observer (ranges of angles of the sundisk, relative to the gaze direction were 20° to 40°). We conducted vertical illuminance measurements using a LMT pocketlux2 lux sensor and high dynamic range (HDR) imaging using a calibrated luminance camera LMK for glare metric calculation, the setup is shown in left part of Fig. 2. These measurements were done under three types of glazing colors on sunny days. The viewing direction towards sun was maintained by adjusting the desk position, so that the eye, the center of the screen(task) and sun position are lying within a plane. Further details of the test room and equipment can be found in [12]. All the measurements were conducted under stable weather conditions with clear sky.

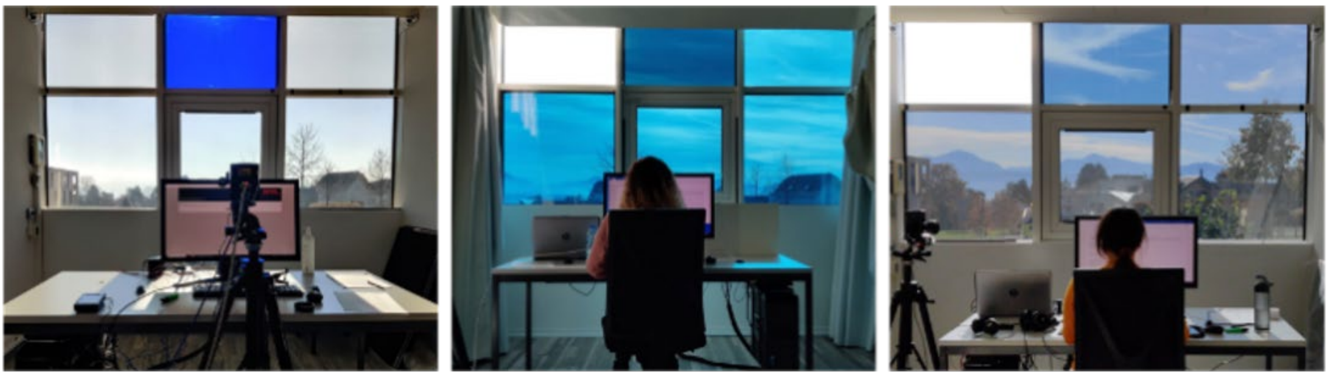
B. Glazing selection

The criteria of choosing three types of glazing spectrum (color) was to have a representation of commercially available and employed glazing types that also exhibit enhanced spectral transmittance under shorter wavelength region where we expect to find the highest impact of replacing $V_{2°}(\lambda)$ with $V_{10°}(\lambda)$. An additional requirement of the glazing characteristic was to reduce the overall transmittance to a level, that one can expect a certain glare protection function (=low transmittance glazing, τ_{vis} ~0.3-2.5%). Due to the characteristics of $V_{10°}(\lambda)$ function, we know that the change in luminance and illuminance (and therefore discomfort glare metrics) of the scene due to the visible sun will only be observed with the glazing that must transmit between 400nm to 550nm. To achieve this, we selected three types of glazing as shown in fig. 2: 1) a color-neutral glazing often used in buildings with glass façade, 2) EC glazing that has blue-tint in its darker state, 3) a saturated deep blue tinted glazing which is meant for specific use cases but have highest sensitivity under short wavelengths compare to the other two types. These three types of glazing are referred as color-neutral glazing, EC glazing and blue glazing in this paper.

The color-neutral glazing was installed as an adhesive film over the window. The film was chosen in a way to not alter the daylight spectrum and maintain natural looking environment inside and outside the room but also has peaks in the short wavelength region where we could expect to see a prominent difference in glare source spectra when using $V_{10°}(\lambda)$.

For the second glazing type, we installed a commercially available electrochromic glazing for its blue tint. EC glazing offers switchable transmittance technology to facilitate daylight modulation. EC material used in such glazing exhibit a spectral shift towards short wavelength region in their darkened state, causing them to appear blue.

For the third type, another blue-colored glazing was installed as an extreme test case having a saturation of 100%, calculated using HSL color model. This type of glazing has limited and specific usage in buildings compared to other two. However, the glazing spectrum was chosen to have peak sensitivity in the region where $V_{2°}(\lambda)$ and $V_{10°}(\lambda)$ differ from each other in order to determine a maximum possible discrepancy in calculation of discomfort glare metrics under daylit conditions ("extreme case").



Blue glazing   Electrochromic glazing   Color-neutral glazing

Figure 2 Tested glazing colors: Saturated blue glazing (left), EC Blue glazing (center), color-neutral glazing (right)

C. *Glazing properties*

Spectral transmittance of all the glazings were measured in a glazing and Nano-technology laboratory on its window test bench. Fig. 3 shows the normalized measured spectral transmittance under visible range for color-neutral, EC and blue glazings. We tested two levels of visible light transmittances for each glazing type listed in Table 1 to evaluate the glare metric variations over a range of conditions. The spectral profile of the glazings are similar for both the transmittances, therefore, we plot normalized spectral transmittance in Fig.3. We report the normal-hemispherical visible light transmittances ($\tau_{v,n\text{-}h}$) of tested windowpane from where the sun was visible. It can be observed from the figure 3 that all our glazing types transmit in the wavelength range (~400nm-525nm) where $V_{10°}(\lambda)$ differs from $V_{2°}(\lambda)$ function.

TABLE 1 Glazing color and tint properties of all three glazing types

Glazing Type	Chromaticity coordinates		HSL values			$\tau_{v,n\text{-}h}$
	x	y	Hue	Saturation	Lightness	
Color-neutral	0.33	0.34	0	0	3.9	0.36%, 1.25%
EC glazing	0.24	0.30	189	65%	5.7	0.6%, 1.6%
Blue Glazing	0.14	0.05	240	100 %	3.3	0.39%, 2.25%

Fig. 4 shows the CIExy chromaticity diagram for all three glazing types depicting how they render the sun in reference to D65 illuminant representing the white point. Chromaticity defines the quality of color on two parameters: its hue and colorfulness, regardless of its luminance. Colorfulness is approximately similar to 'saturation' in HSL color model. Table 1 lists the chromaticity coordinates for each glazing type corresponding to the Fig. 4. It also lists the hue, saturation and lightness value of HSL color model. The saturation or the purity of color is highest for blue glazing at 100%.

It should be noted that these three glazing colors are of different low visible light transmittance from each other as reported in Table 1. These transmittances were designed for other independent experimental studies. Since in this study we only compare the glare metric and luminance values within each glazing color and not across, therefore, the different transmittances are not of concern. Also, within each glazing spectrum, the spectral profile remains the same for different transmittances.

D. *Glare metrics*

Discomfort glare metrics for daylit conditions generally account for either contrast or saturation effects or both effects in case of hybrid metrics. Both contrast and saturation terms in the glare metrics are affected by the replacement of $V_{2°}(\lambda)$ with $V_{10°}(\lambda)$ function due the change in photometrics quantities: glare source and background luminance and the vertical illuminance at eye (E_v). We evaluate two glare metrics- Daylight Glare Probability (DGP) [13] and CIE Glare index (CGI) [14] based on hybrid and contrast effects, respectively, and compare the values weighted using $V_{2°}(\lambda)$ with $V_{10°}(\lambda)$ functions. The glare metric equations are shown in the Eq. 1 and 2, where we replaced the Luminance, E_v and E_{dir} in the equation weighted by $V_{10°}(\lambda)$. Studies have shown that these two metrics are reliable in predicting glare in typical daylit workplace conditions and also under electrochromic glazing [12], [15].

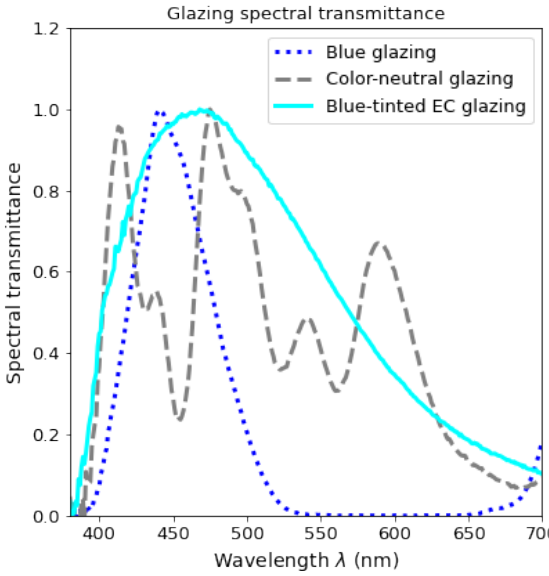


Figure 3 Normalised spectral transmittance of color-neutral, EC and blue glazing under visible range

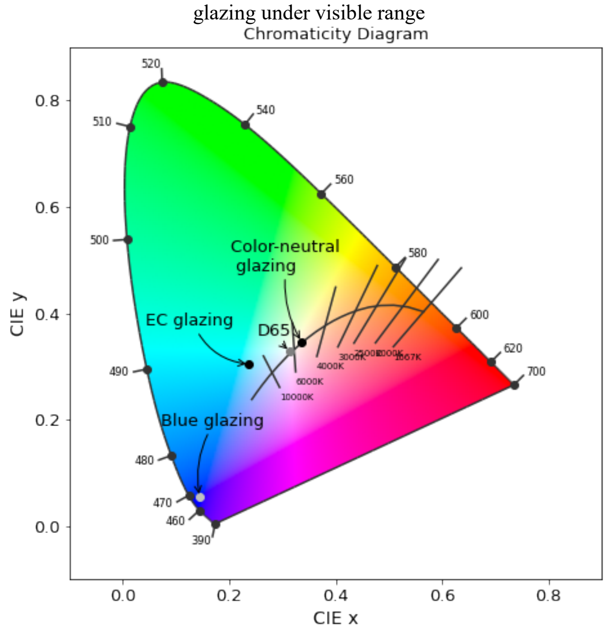


Figure 4 CIE xy chromaticity coordinates of the sun filtered by all three glazings in reference to illuminant D65

Equation 1:

$$DGP = 5.87e^{-5}\,\boldsymbol{E_v} + 9.18e^{-2}\log\left(1 + \sum \frac{\boldsymbol{L^2\omega_{5.8°}}}{\boldsymbol{E_v^{1.87}P^2}}\right) + 0.16$$

Equation 2:

$$CGI = 8 * \log 2 * \frac{\boldsymbol{1+E_{dir}/500}}{\boldsymbol{E_v}}\left(\sum \frac{\boldsymbol{L^2\omega_{5.8°}}}{\boldsymbol{P^2}}\right)$$

where E_v is vertical illuminance at eye level, L is luminance of glare source weighted by $V_{2°}(\lambda)$ or $V_{10°}(\lambda)$ functions, ω is solid angle of the glare source (=0.00804651 sr), P is the position index of the glare source, E_{dir} is the direct vertical illuminance at eye level.

E. *Photometric measurements and calculations*

Measurements of vertical illuminance and HDR capture of glare scenes were conducted on sunny days. For color-neutral glazing, we collected 50 datapoints under two transmittances (total 100 datapoints), for blue glazing 25 datapoints for two transmittances (total 50 datapoints) and for EC glazing 20 datapoints were collected under two transmittances (total 40 datapoints). Discomfort glare was calculated for the low sun position indices (P<4) to have sun always within central visual field but not in the fovea. This was chosen to create critical glare scenarios in workplace environment where we could observe the maximum difference, if any, between $V_{2^\circ}(\lambda)$ and $V_{10^\circ}(\lambda)$ weighted glare metrics.

Since the measuring equipment used in this study employ a $V_{2^\circ}(\lambda)$ function to measure illuminance and capture HDR imaging, and due to the lack of spectral imaging and measurements, a reference standard solar spectra provided by ASTM G173-03 [16] was used to create the sun spectrum. We used the standard direct solar (+circumsolar) spectrum defined by ASTM G173 for 5.8° diameter (solid angle ω= 0.00804651 steradians) around the sun. The integrated power density of this spectrum is 855 W/m^2 which was scaled to match the on-site measured solar irradiance at the time of measurements for a range of 400nm to 2700nm. The resulted solar spectra were then integrated with the measured spectral transmittances of the glazings. The sun luminance weighted over $V_{2^\circ}(\lambda)$ and $V_{10^\circ}(\lambda)$ was calculated as per Equation 1.

$$L_{2^\circ or\ 10^\circ} = \mathrm{K}_m \int_{380}^{780} \mathrm{E}_\lambda * \mathrm{T}_\lambda * V_{2^\circ or\ 10^\circ}(\lambda) d\lambda$$

Equation 1

where $L_{2^\circ or\ 10^\circ}$ is luminance of the glare source weighted by $V_{2^\circ}(\lambda)$ and $V_{10^\circ}(\lambda)$ K_m is the photopic luminance efficacy value, E_λ is the scaled spectral irradiance of the sun based on ASTM spectra [16], T_λ is the measured spectral transmittance of glazing.

To further validate this method, we compared the above calculated luminance values using $V_{2^\circ}(\lambda)$ weighting function with the luminance derived from the HDR images captured with a luminance camera that employs $V_{2^\circ}(\lambda)$ filter. We found that the normalized RSME errors stayed within an acceptable range of 15%.

In a similar way, we also calculated the vertical illuminance at eye level weighted by $V_{2^\circ}(\lambda)$ and $V_{10^\circ}(\lambda)$ functions. For calculating the direct part of vertical illuminance which is contributed solely by the sun, we followed same approach as mentioned above for the sun luminance calculation. Direct vertical illuminance values derived from the HDR images using the Evalglare [17] tool in Radiance [18] for a 5.8° sun were scaled by a factor of L_{10°/L_{2° to get the illuminance weighted by $V_{10^\circ}(\lambda)$ function. For the total vertical illuminance at eye level, we incorporated measured spectral irradiance profile at eye level for all the glazing configuration using the spectrophotometer data and weighted the total spectral irradiance by $V_{2^\circ}(\lambda)$ and $V_{10^\circ}(\lambda)$ and scaled it to match the measured vertical illuminance at eye.

Evalglare was further used to derive the position index P of the sun from the HDR images. The adjusted glare metrics (DGP and CGI) were calculated as per Eq. 1 and 2 by replacing the illuminance and source luminance values in the equations with the adjusted values weighted based on $V_{2^\circ}(\lambda)$ and $V_{10^\circ}(\lambda)$ functions.

III. Results

A. Relative spectral power distribution

Fig. 5-7 shows the normalized spectral power distribution of the sun (serving as glare source) visible through the color-neutral glazing, EC glazing and blue glazing, respectively. It can be observed from the figures that the difference between the glare source spectra weighted with $V_{2^\circ}(\lambda)$ and $V_{10^\circ}(\lambda)$ is maximum in case of blue glazing (fig. 7). In case of EC glazing, even though it has blue-tint we do not observe significant difference between the two functions (fig. 6). Similarly, for color-neutral the difference is not significant.

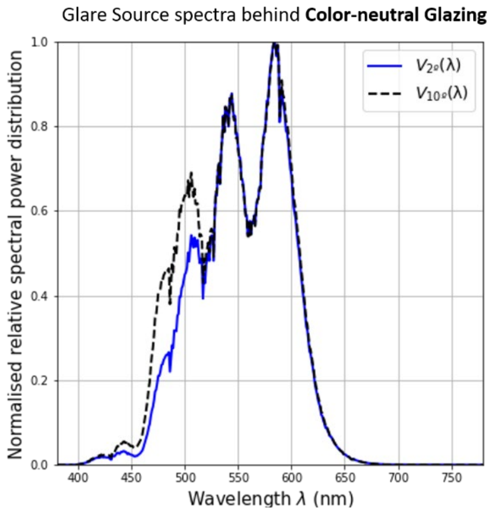


Figure 5 Normalised relative spectral power distribution for color-neutral glazing weighted by $V_2(\lambda)$ and $V_{10}(\lambda)$ functions

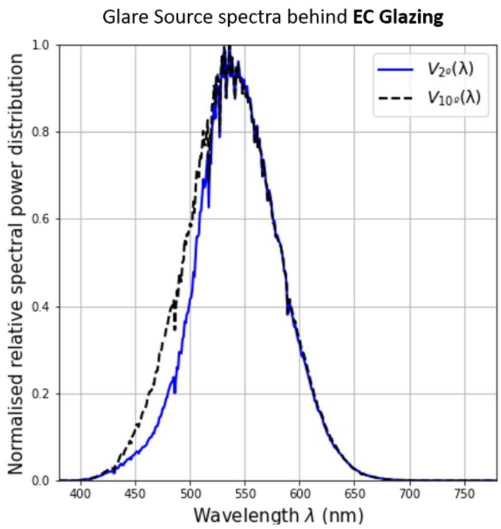


Figure 6 Normalised relative spectral power distribution for EC glazing weighted by $V_2(\lambda)$ and $V_{10}(\lambda)$ functions

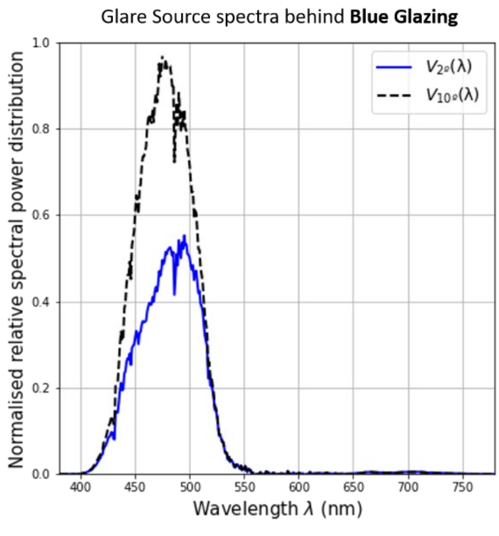


Figure 7 Normalised relative spectral power distribution for blue glazing weighted by $V_2(\lambda)$ and $V_{10}(\lambda)$ functions

TABLE 2 Mean values of glare metrics and sun luminance based on $V_{2°}(\lambda)$ and $V_{10°}(\lambda)$ functions

Glazing type	*Mean DGP*		Mean CGI		Mean Sun Luminance	
	$V_{2°}(\lambda)$	$V_{10°}(\lambda)$	$V_{2°}(\lambda)$	$V_{10°}(\lambda)$	$V_{2°}(\lambda)$	$V_{10°}(\lambda)$
Color-neutral	0.32	0.33	28.6	28.8	67583	70448
EC glazing	0.34	0.35	35.4	35.7	94283	98494
Blue Glazing	0.34	0.41	33.2	36.2	98467	166883

Table 3 Wilcoxon p-values and mean relative differences between the two groups based on $V_{2°}(\lambda)$ and $V_{10°}(\lambda)$ functions for evaluates metrics under three glazing colors

Glazing type	*DGP*		CGI		Sun Luminance	
	p-value	Mean relative diff.	p-value	Mean relative diff.	p-value	Mean relative diff.
Color-neutral	0.27	3%	0.6	0.7%	0.18	4%
EC glazing	0.54	3%	0.7	0.8%	0.36	4.5%
Blue Glazing	***1.6e-5***	***20%***	***3.6e-3***	***9%***	***2.4e-5***	***70%***

B. *Luminance*

Fig. 8 presents the comparison of the luminance of the visible sun calculated based on $V_{2°}(\lambda)$ and $V_{10°}(\lambda)$ for all three glazing colors with the median values in the boxplots. Table 2 reports the mean values of each evaluated metric for $V_{2°}(\lambda)$ and $V_{10°}(\lambda)$ functions. The observed spread in the boxplots are due to two levels of visible light transmittances being tested in each of the glazing spectra.

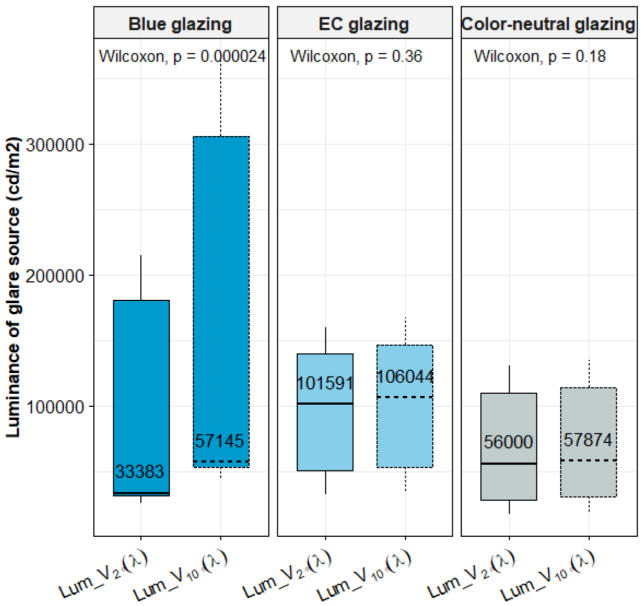


Figure 8 Box plots with median values showing the comparison between $V_2(\lambda)$ and $V_{10}(\lambda)$ functions in quantifying luminance

We applied Wilcoxon ranked sum test [19] to perform pairwise comparison between the two groups of luminance values weighted by $V_{2°}(\lambda)$ and $V_{10°}(\lambda)$ to determine if there is a significant difference at α=0.05 between these two groups in each glazing category (Fig. 8 and Table 3). We also calculated a mean relative percentage difference between these two groups as reported in Table 3.

The difference of the sun luminance is not significant for color-neutral (p=0.18) and EC glazing (p=0.36), however, it is statistically significant for the blue glazing with a p=0.00024 with an effect size of 0.44 indicating a moderate effect. The mean relative percentage differences between the luminance are around 4% for EC and color-neutral glazing, whereas for blue glazing the difference is 70%. These results indicate that for color-neutral and EC glazing, that are more often employed in buildings, replacing $V_{2°}(\lambda)$ with the $V_{10°}(\lambda)$ has minimal impact on the luminance. However, same doesn't hold true for saturated blue glazing where we observe highly substantial difference in luminance that can entirely transform the glare scenario.

C. *Discomfort glare*

Fig. 9 and 10 demonstrate the comparison of glare metrics DGP and CGI based on $V_{2°}(\lambda)$ and $V_{10°}(\lambda)$ functions under three different glazing spectra. Similar to luminance results, we observe a statistically significant difference ($p<0.05$) only in the blue glazing for both the glare metrics. The difference is not significant for EC and color-neutral glazing. Wilcoxon p-values are reported in Table 3 along with the mean relative difference which are again negligible for color-neutral and EC glazing compared to the blue glazing. In case of blue glazing, the difference in mean DGP values (Table 2) between the $V_{2°}(\lambda)$ and $V_{10°}(\lambda)$ are equivalent to one category difference of achieved comfort from glare as defined by EN17037 [20]. Similarly, for CGI the difference in mean metric values can create a large difference of 9%. In comparison to the relative luminance differences, the impact of replacing $V_{2°}(\lambda)$ with $V_{10°}(\lambda)$ on glare equations are rather small due to the logarithmic function over the luminance in the glare equations.

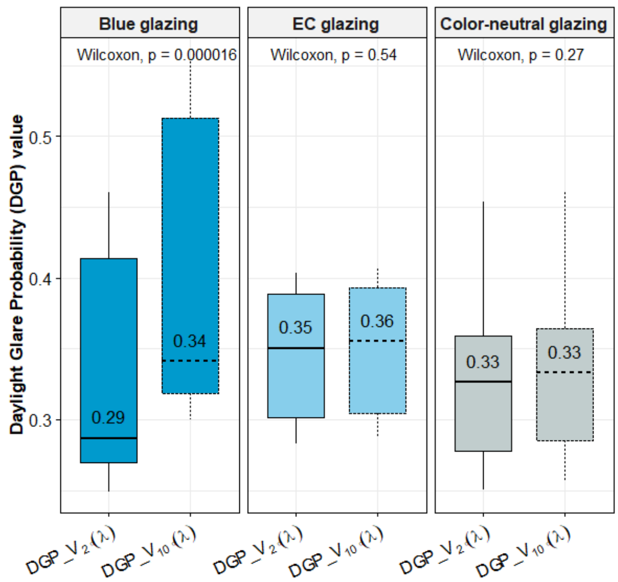


Figure 9 Box plots with median values showing the comparison between $V_2(\lambda)$ and $V_{10}(\lambda)$ functions in quantifying DGP metric

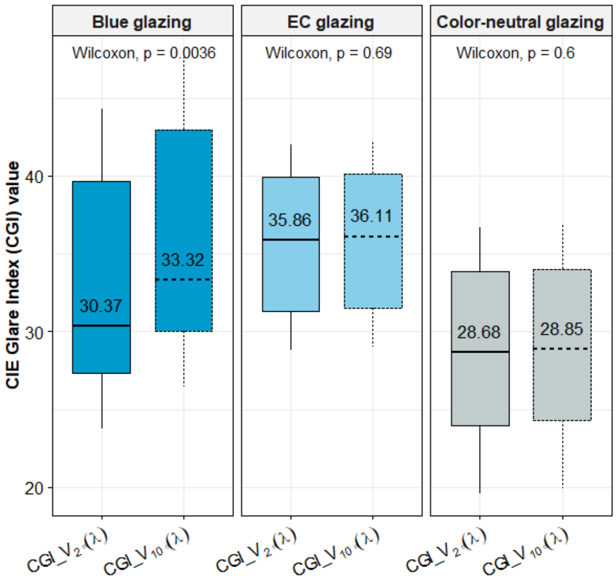


Figure 10 Box plots with median values showing the comparison between $V_2(\lambda)$ and $V_{10}(\lambda)$ functions in quantifying CGI metric

IV. Discussions

It should be noted that in this paper we purely focus on the quantitative difference between using 2 degree and 10-degree functions. The subjective perception of occupants under colored glazing and glare sources should be evaluated to determine if any of these two functions are applicable under non-neutral daylit conditions. Previous studies with vehicular headlamps have suggested the inability of conventional photopic luminosity functions (both $V_2(\lambda)$ and $V_{10}(\lambda)$) in defining the glare perception of users under blue colored LEDs and possibility of including s-cone sensitivity to modify the $V(\lambda)$ for both 2- and 10-degree glare sources [22]–[26]. There is a need to evaluate impact of color under daylit glare scenarios to further elucidate on these findings.

Some limitations of this study are that due to the lack of measuring instruments and measurements available based on $V_{10}(\lambda)$, we implement a calculation method that uses standard sun spectra that could differ from actual onsite sun spectra due to the atmospheric conditions and this can create discrepancies to some extent in the calculated glare metric values using this method. However, since we perform a relative comparison between the glare metrics based on $V_2(\lambda)$ and $V_{10}(\lambda)$, these discrepancies can be ignored. We also made sure to conduct the measurements only during stable weather conditions with clear sky.

It should also be noted that the results found in this study are only applicable for the broad-spectrum daylight sources and can vary for narrow spectrum and monochromatic light sources. Although the method described in this paper can be extended to electric light scenarios as well. The spectrum profile of the luminaries and the peak wavelength of the spectra play a key role in determining whether using $V_{10}(\lambda)$ would make a large impact on glare metrics.

V. Conclusion

We found that the mean relative difference between the sun luminance calculated using $V_2(\lambda)$ and $V_{10}(\lambda)$ ranges between 4% to 5% for the color-neutral and EC glazing, whereas the difference lies between 68% to 70% for the saturated blue glazing and is statistically significant. The mean difference in daylight glare probability (DGP) calculated using $V_2(\lambda)$ and $V_{10}(\lambda)$ is 3% for both color-neutral and EC glazing, whereas for the blue glazing the difference is 20%. Calculated CGI metric values differ by 0.7% and 0.8% in case of color-neutral and EC glazing, whereas for the blue glazing the difference between CGI calculated based on $V_2(\lambda)$ and $V_{10}(\lambda)$ is 9% and is statistically significant.

From these results, we can conclude that even though the $V_{10}(\lambda)$ luminosity function represents a physiologically more accurate quantification of the luminance in the parafoveal field, the difference in achieved discomfort glare metrics based on this function for the more often employed color-neutral and EC glazing are negligible compared to the conventionally used $V_2(\lambda)$. However, the user perception of glare under blue EC glazing in comparison to color neutral glazing is suggested to be higher [27] which is not explained by the replacement of $V_2(\lambda)$ with $V_{10}(\lambda)$ in the glare equations as shown in this study. We need further modification into photopic luminosity function and thereby in the current glare metrics to include the impact of color on glare perception. We also found that if the sun is filtered by saturated blue glazing that peaks at 450nm, the $V_{10}(\lambda)$ function provides much higher discomfort glare metrics values and therefore, indicate high level of perceived discomfort which needs further investigation through subjective assessment under such glazing spectrum.

Acknowledgment

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Effect of window glazing color and transmittance on human visual comfort

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ABSTRACT: Occupants' visual comfort in an indoor space strongly depend on the quantity and quality of the daylight inside the space which can be altered with the type of window glazing. In this study, we compared the visual comfort perception of participants with sun in their field of view under two types of glazing: color-neutral and blue-tinted electrochromic glazing. The main experimental variables are the color and visible light transmittances of the glazing. The aim was to determine the influence of these variables on participants' discomfort glare, view out and color perception. We found that the discomfort glare was perceived more strongly with blue-tinted glazing compared to the color-neutral glazing for a range of (low) transmittances. We also found that the colors of outdoor elements were rated non-natural in case of blue-tinted glazing compared to color-neutral glazing. The outside view was perceived more restricted in blue-tined glazing compared to color-neutral glazing even though both of them maintain view clarity.
KEYWORDS: Visual comfort, Daylight, Window glazing, Color, Glare

1. INTRODUCTION

Windows and shading devices play a key role in allowing sufficient daylight into the buildings and providing a view to the outside. Current developments in the switchable electrochromic (EC) glazing technology facilitate daylight modulation for better thermal and visual comfort while maintaining the view to the outside [1], [2]. Electrochromic materials employed in commercially available smart glazing technology exhibit a spectral shift towards short wavelengths range in their darkened state, causing them to appear blue [3]. Therefore, the usage of this technology may alter the spectrum and the correlated color temperature of daylight inside the space, which have been shown to influence human visual comfort and health [4]–[6]. Previous studies on switchable electrochromic glazing have reported their positive influence on thermal and visual comfort, their capability in controlling glare and associated user satisfaction [7][8]. Studies have also shown that occupants prefer color-neutral illumination to ensure natural looking environments [9], [10]. With the recent developments in EC materials to improve the color-neutrality of the switchable glazing in the dark state, it seems plausible that the alteration of daylight spectra is minimized while further reducing the transmittance for glare control [11], [12]. To our knowledge, there are currently no studies comparing the visual comfort perception of blue-tinted EC glazing with color-neutral glazing at low transmittance levels.

To address this gap, we conducted a between-subject study under blue-tinted EC glazing and color-neutral glazing of different low transmittance levels to investigate the effect of glazing color and transmittance on occupants' visual comfort perception. For the blue-tinted glazing, we installed a commercially available EC glazing, whereas to create color-neutral glazing, we installed color-neutral window films with low transmittance on clear acrylic panels fixed to a double-pane glazing. We evaluated and compared participants' responses to lighting environment, discomfort glare, color rendering, and view clarity to the outside under the blue-tinted EC glazing and color-neutral glazing.

2. METHOD

2.1 Experiment Design

A between-subjects study involving 20 participants in blue-tinted EC glazing and 55 participants in color-neutral glazing was conducted in a South-facing semi-controlled daylit office-like environment from 2019 to 2021. Experiments were conducted during the winter months under sunny conditions to benefit from low sun angles, thereby enabling to have the sun as the only glare source visible in the participants' central field of view (FOV). The experimental setup and glazing configuration are shown in Fig.1.

We exposed the participants to four experimental conditions in the blue-tinted and color-neutral glazing systems. In this article, we analyse three experimental conditions from each of the glazing type to have similar experimental scenarios for comparisons purpose. To create the conditions, we only varied the transmittance of the windowpane through which the sun was visible to the participants ("Sun Window" in Fig.1). We evaluate three levels of transmittance under blue-tinted glazing (τ_v = 0.14%, 0.6%, 1.6%) and the color-neutral glazing (τ_v = 0.36%, 1.25%, 3.4%). These experimental conditions are labelled as B1, B2, B3 for blue glazing and N1, N2, N3 for the color-neutral glazing in the increasing order of their sun window transmittances. Their properties are listed in Table 1.

Figure 1 Participants performing the tasks in blue-tinted glazing (left) and in color-neutral glazing (right)

The top-right windowpane was kept at maximum transmittance to allow sufficient daylight ("Daylight window" in Fig.1.) and to minimize the effect of low color-rendering inside the room. The remaining of the four window panes were kept at constant transmittance of 3.7% for blue-tinted glazing and 4.8% for color-neutral glazing. As our initial design intention was to keep the color-neutral and blue-tinted glazing at the same level of transmittance, we made sure to order color-neutral glazing with similar transmittance values as the blue EC glazing. However, when confronted with our findings, we measured the spectral transmittances of the EC glazing in a dedicated glazing and nano-technology lab facility. The measured transmittance values were found to be substantially lower than the ones received from the EC manufacturers. This explains the difference in τ_v values between the two experiments.

The room temperature and desk illuminance levels were constantly measured during the experiments and were kept within recommended levels to have constant conditions and avoid any confounding effects. However, the ambient lighting conditions were slightly higher in case of neutral glazing owing to the higher window transmittance as stated above. A manufacturer-calibrated HDR camera with a 180° fish-eye lens and equipped with a vertical lux sensor was used to capture

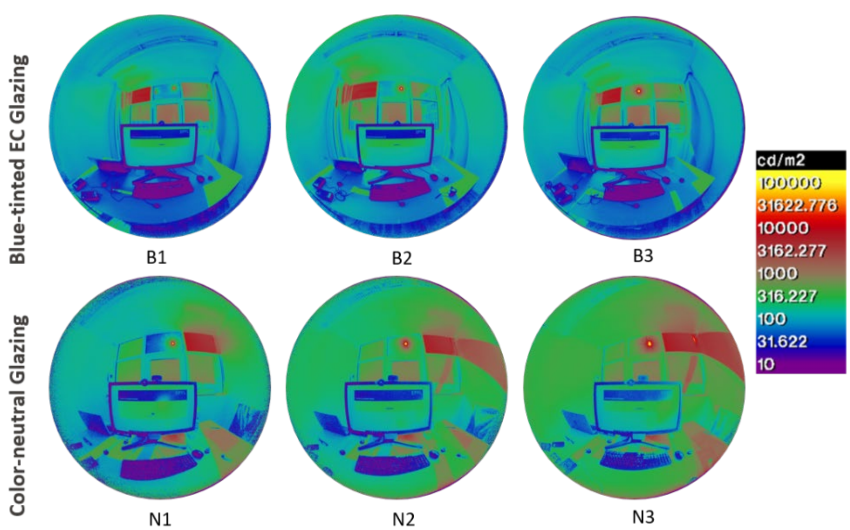

Figure 2 Falsecolor images of the test conditions shown to the participants with changing visible light transmittance of the sun window for blue-tinted and color-neutral glazing

the luminance distribution in the field of view and record vertical illuminance at eye level. Figure 2 presents a sample of captured falsecolor luminance HDR images of the experimental scenes. A spectrometer was installed behind the screen looking towards the window to record the spectral irradiance inside the room near participants' view point. Further details on the test room setup can be found in [8].

2.2 Experiment protocol

The experiments were conducted in the morning until early afternoon for two hours per participant on clear sky days. Participants were first briefed about the protocol and then answered some background questions about their demographics and indoor environmental preferences. Afterwards, they were exposed to four test conditions in randomized order to avoid any order bias. Their desk position was rotated for each scene in a way to keep the sun always in their central FOV. Each scenario was preceded by a break (~ 5-10 minutes), where they wore an eye mask to dark adapt, during which researcher took the measurements and changed the glazing transmittance to prepare the room for next scenario. The exposure duration to each condition was about 15 minutes.

During the exposure time, participants were given a typing task that allowed them to visually adapt to each condition. Afterwards, they filled a questionnaire reporting their level of comfort. Participants evaluated discomfort glare, lighting levels, color perception and view clarity associated with each scenario on different rating scales. During the break, we captured HDR images of each experimental condition from participant's eye height and measured respective vertical illuminance. The falsecolor HDR images of the scenes are presented in the Figure 2. These images were later processed to derive the scene luminance maps and calculate glare metrics using evalglare (v. 3.02)[13].

2.3 Subjective questionnaires

Participants answered an online survey questionnaire about the discomfort glare, view out perception and color perception after exposed to each testing condition. These questions were answered on the binary, categorial (Likert) or ordinal scales adapted from the previous visual comfort studies [14]–[16] with an aim to minimize the potential response bias that can be created by the rating scales. We analysed the responses pertaining to discomfort glare, color perception and view out in the subsequent section.

3. RESULTS AND DISCUSSION

3.1 Experiment conditions

We performed statistical analysis on the cleaned dataset after removing the datapoints with unstable weather conditions and ensuring stable conditions throughout all the experiments. Table 1 summarizes the visual properties of all the experimental conditions under blue-tinted and color-neutral glazing and the percentage of participants reporting discomfort in each condition.

Table 1 Summary of the data measured for all the experimental conditions.

	Scene	Glazing τ_v	Mean DGP	Mean E_v (lux)	Mean CCT (in K)	% of ppl reporting discomfort
Blue-tinted EC glazing	B1	0.14 %	0.32	670	8627	16%
	B2	0.6%	0.41	1050	9783	53%
	B3	1.6%	0.50	1650	10427	89%
Color -neutral glazing	N1	0.36 %	0.35	1770	5320	17%
	N2	1.25 %	0.44	2200	5308	36%
	N3	3.4%	0.54	3300	5372	78%

The mean Daylight Glare Probability (DGP) values derived from the captured HDR images directly relate to the glazing transmittance, while the mean Correlated Color Temperature (CCT) values calculated from the measured spectral irradiance relate to the overall color inside the room measured near participant's view point. The ambient lighting levels are represented by the total vertical illuminance (Ev) measured at eye level. We can assess that the ambient lighting was a higher in case of neutral glazing due to the higher window transmittances. While the measured CCT values are higher in blue-tinted glazing conditions compared to the color-neutral conditions that has similar CCT for all four conditions.

3.2 Discomfort Glare perception

Figure ***3*** and Figure **4** shows the percentage of subjective votes experiencing discomfort glare on 'Yes/No' scale under all the glazing transmittances for blue-tinted and color-neutral glazing respectively. It can be observed from the figures that scene B1 with sun window transmittance 0.14% performs best in minimizing discomfort from glare for 84% of the participants under blue-tinted glazing, whereas similar or lower level of comfort can be achieved under color-neutral glazing for the scene N1 with sun window transmittance of 0.36%. The DGP value is higher for N1 scene compared to B1 scene indicating that the glare should have been perceived higher in color-neutral glazing, however, we observe that people are tolerating glare better under color-neutral glazing compared to blue EC glazing. We can observe similar trends for all the remaining experiment scenes, e.g., comparing B2 of blue-tined glazing where 53% of participants are reporting discomfort with the N2 of color-neutral glazing where only 36% of participants are reporting discomfort which has higher mean DGP values.

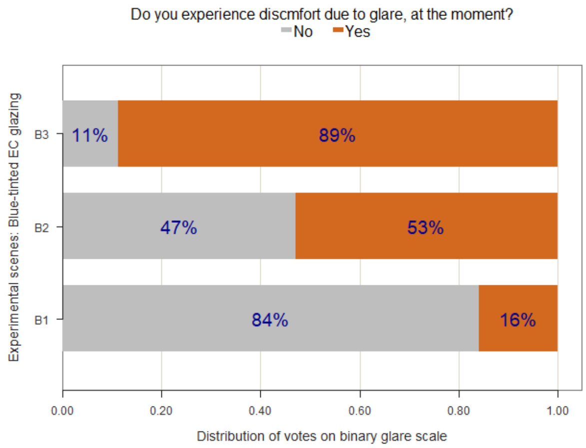

Figure 3 Glare vote distribution under blue-tinted glazing for three different glazing transmittances

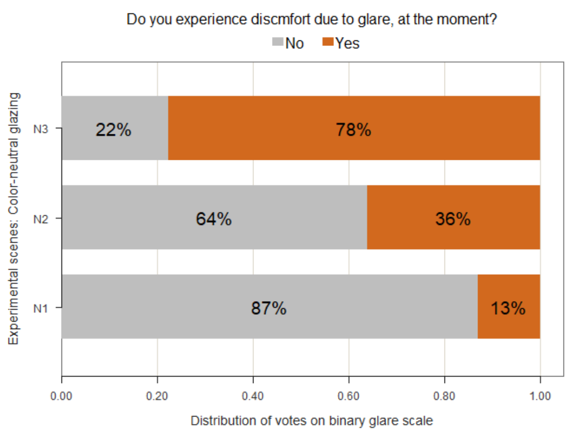

Figure 4 Glare vote distribution under color-neutral glazing for four different glazing transmittances

To further validate these findings, we calculated DGP threshold values using the closest topright method in precision-recall curves [17], which are the borderline values between the comfort and discomfort. We found higher threshold value for color-neutral glazing (DGP=0.48) compared to blue-tinted glazing (DGP=0.40), which led us to conclude that the glare was perceived as stronger with the blue-tinted glazing.

3.3 View Out perception

Participants rated the clarity of the view out through the glazing on a 10-point scale from not clear at all to very clear. The outside view was the same for both the color-neutral and blue-tinted glazing type since the test rooms were located next to each other. In case of color-neutral glazing, view to the outside was rated as not clear in 18% of the cases whereas in blue-tinted glazing view was rated as restricted or not clear in 37% of the cases. This is surprising since both types of glazing maintain a clear view to the outside. It could be due to the blue-shift if we consider that blue-tinted glazing may have a negative impact on how clearly the outside view is perceived. This is not really reinforced, however, by the answers regarding satisfaction with outside view, which was rated similarly in both the glazing types with 75% satisfaction in blue-tinted glazing and 77% in color-neutral glazing. We should also note the limitation that the window transmittances were slightly different in color-neutral glazing compared to the blue-tinted glazing which could affect the comparison of view out perception between the two glazing types.

3.4 Color perception

As observed in Table 1, blue-tinted glazing has much higher CCT compared to the color-neutral glazing. The quality of the color in blue-tinted glazing and color-neutral glazing is demonstrated in Figure 6 in terms of the average chromaticity coordinates of the test conditions in comparison to the CIE D65 illuminant representing the white point.

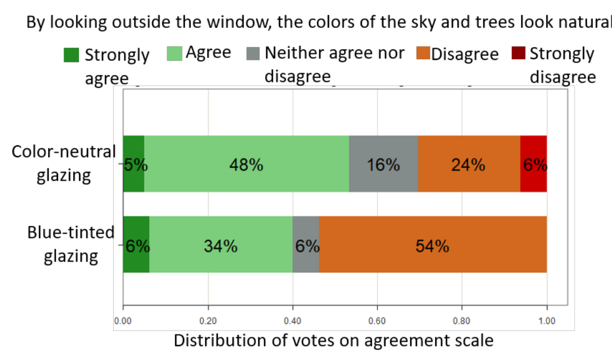

Figure 5 Votes on the color perception of the outdoor environmental elements

As shown in *Figure 5*, the colors of the outdoor elements rendered by the blue-tinted glazing were found to be non-natural by 54% of the participants whereas in color-neutral glazing the colors were reported non-natural by 30% of the participants. The colors of the indoor elements were rated as natural in both blue and color-neutral glazing by a majority of participants. This can be explained by the strategy of having a daylight window at maximum transmittance that allows the daylight inside the room without altering its color.

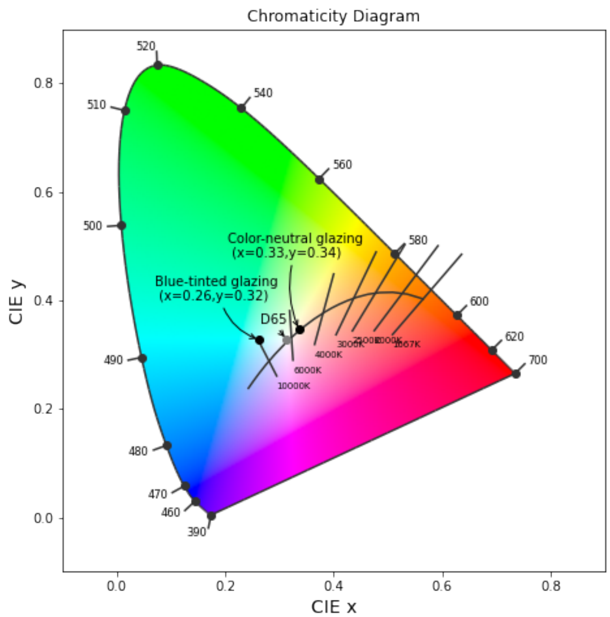

Figure 6 Chromaticity coordinates (x, y) representing the experimental scenarios (mean values) for blue-tinted and color-neutral glazing with the blackbody locus.

4. CONCLUSION

This study evaluated the occupants' perception of visual comfort and quality aspects of a daylit office-like test room with blue-tinted and color-neutral glazing. We found that the colors of the outdoor environment were not perceived natural in blue-tinted glazing compared to color-neutral glazing for a majority of participants. The view to the outside was voted as being clearer in color-neutral glazing compared to blue-tinted glazing, even though both glazings maintain a clear view to the outside. The color-neutral glazing performed better than the blue-tinted glazing in minimizing discomfort from glare when the sun is in the field of view of the participants. A τ_v = 0.14% was required in case of blue-tinted glazing to provide comfortable conditions to the majority (=84%) of participants, whereas a similar level of comfort was reached under color-neutral glazing at τ_v = 0.36%. This finding might have an origin in a combination of psychological and physiological factors related to color vision of human eye. Further investigations are required to elucidate these results.
The results of the study provide valuable insights for the building façade industry. They suggest that the development goals for the switchable glazing technology should be towards improving the color-neutrality for achieving user satisfaction and better glare control.

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Transmittance thresholds of electrochromic glazing to achieve annual low-glare work environments

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Abstract

A recent study on the glare protection performance of electrochromic (EC) glazing showed that visible transmittance levels lower than 0.6% are necessary to achieve comfortable situations for sun positions, that were close to the central field of view. However, the question that arises is how often such situations occur throughout the year and how the glare protection performance of EC systems is for typical office situations for different climates and orientations. This study aims to quantify the annual performance for such configurations by applying improved simulation methods to conduct annual glare simulations and comparing them to the EN17037 classifications. The enhancement of the simulation method compared to existing methods was necessary to correctly consider the blurring effect in the lens of the eye – neglecting this would lead to an overestimation of glare.

We found that for mid and north European climates the extreme situations do not occur such often, so that the EC-glazing systems being able to switch to transmittance levels of 1% can mitigate glare throughout the year reasonably well for typical office situations and reaches typically the highest glare protection category according to EN17037 for a viewing direction, that is parallel to the facade. For more sunny climates such as Rome, slightly lower transmittance levels (around 0.5%) would be necessary to achieve a similar glare protection level.

The study also revealed that tables E.7 and E.8 of EN17037 with pre-calculated 95-percentile Daylight Glare Probability (DGP) values should be re-calculated.

Introduction

Electrochromic glazing (EC) is an emerging window technology that is applied to buildings to control solar radiation penetration for energy savings and thermal comfort (Ajaji & André, 2015; Piccolo, 2010). With its switchable transmittance technology, it offers control over the visual environment as well and therefore, can help in mitigating glare from daylight (Piccolo & Simone, 2009). There has been several studies based on simulations, physical measurements and occupant surveys to evaluate the capability of EC glazing in controlling discomfort glare (Clear et al., 2006; Jain et al., 2021; Lee & DiBartolomeo, 2002; Moeck et al., 1996). A recent user-assessment study (Jain et al., 2022) investigated the performance of such a façade system in terms of glare protection and found that it needs to be switched to transmittance levels below 0.6% to achieve comfortable situations if the sun is located in the central region of the field of view. Furthermore, the same study showed that 0.6% transmittance can achieve comfortable situations when the sun is in the peripheral field of view. The question that arises is: What should the annual glare protection performance of electrochromic glazing for typical workplace configurations be in different contexts? This study aims to answer that question and applies advanced annual glare simulations on different desk positions (distances from the window) and viewing directions, different orientations of the building and different geographic locations across three latitudes.

The European standard EN17037 that sets the requirements for providing adequate daylight into buildings (European Committee for Standardization CEN, 2019) also defines different levels of glare protection. Tables in its appendix provide precalculated 95-percentile Daylight Glare Probability (DGP) values for different orientations and climates, that should support planners to select appropriate transmittance levels to achieve the desired glare protection levels. However, the method applied to derive these values (the main author of this study was involved in deriving the tables in the standard) is ignoring the intraocular light scattering and therefore an overestimation of glare is expected.

In this study, with more accurate and sophisticated simulation methods we run simulations for the same geometry and climates in order to determine the needed transmittance levels of electrochromic glazing to meet the three comfort levels given by the EN17037 (low, medium and high). These outcomes support decision-making when it comes to building and workplace design using electrochromic glazing and help in setting boundaries if one wants to achieve low-glare environments with the use of such technology in different latitudes.

Method

Glare metric

For this study, the Daylight Glare Probability (DGP) metric is used to predict glare (Wienold & Christoffersen, 2006), as it is also used in EN17037 to define glare protection criteria. Several studies showed, that this metric is reliable to predict glare in typical workplace situations (Jakubiec & Reinhart, 2012; Wienold et al., 2019) and specifically also for the usage of electrochromic glazing (Jain et al., 2022). For annual data on timestep-basis, we apply the method of EN17037 that uses the 95-percentile-value of the occurring DGP values during an assumed usage time between 08h-18h (note that in EN17037 this is the definition of "$DGP_{e<5\%}$").

Simulation method

To generate hourly DGP data, we applied a newly developed climate-based glare simulation method – the Adaptive Glare Coefficient method or AGC (Wienold & Andersen, 2022) – that uses hourly timesteps and is a speed-improved successor method of eDGPs (Wienold, 2009), showing similar behaviour and accuracy (Wasilewski et al., 2022).

Both methods (AGC and eDGPs) are based on RADIANCE (Ward, 1994) as the core rendering engine. The vertical illuminance E_v, a necessary input for both AGC and eDGPs, was calculated using Daysim. As most of the climate based daylight modelling tools (CBDM), the applied method relies on the Perez all weather sky model (Perez et al., 1993) for the sun and sky modelling.

Sun blurring

One crucial point for simulating glare when the sun is visible for the observer is the optical modelling of the "seen sun". While the simulated sun is a perfect disk with a view angle of 0.533°, the sun disk appears differently when in the field of view, due to the intraocular light scattering. Captured High Dynamic Images (HDR) images show a blurring effect, which is actually quite similar to what happens in the eye, where intraocular (forward) light scatter and internal reflections cause flare and an increase of the apparent size of the glare source. From an energy point of view, this blurring effect does not matter much since the energy flux remains nearly identical and, as a result, the core physical rule of energy conversion is kept. However, when it comes to the calculation of glare metrics, the blurring effect does matter due to the fact that most glare metrics including DGP use $L^2 \cdot \omega$ in their equation, while energy conservation follows $\sim L \cdot \omega$. The study at the basis of DGP used an HDR camera with a fish-eye lens that also caused the blurring of the sun – in other words, the "correct" calculation of DGP requires an image which blurs the sun. As consequence, a non-blurred sun in an HDR-image would automatically cause an overestimation of the glare.

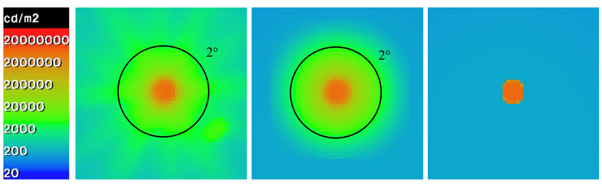

Figure 1: Visible sun behind EC glazing:
Left: Captured HDR image
Middle: Rendered image with sun blurring
Right: Rendered image without sun blurring

For that reason, we consider it necessary to integrate a blur effect in glare simulations if the sun disk may be visible in the field of view.

This was done in the AGC method, which has implemented a blurring feature based on Gaussian functions, which simulates a Lorentzian function with FWHM=11, introduced by (Ward et al., 2021).

In figure 1, we can visualize the luminance distributions around the sun disk for an HDR image, a simulation with and without blurring of the sundisk.

Figure 2 shows the energy flux as function of the integration angle around the sun direction for the captured HDR vs. the simulation, and illustrates that the Lorentzian approximation function follows closely the behaviour of the captured HDR image. It shows further, that within a 2° angle (=opening angle) around the sun direction (also illustrated in figure1), 98% of the sun + circumsolar (10°) energy is concentrated. Using *evalglare* to derive DGP from an image, it extracts peaks above a threshold of 50kcd/m^2 with its default setting, which translates for typical EC-situations to an angle of around 1° around sun direction for the extracted peak. Therefore, the Gaussian approach reproduces nearly an identical glare source compared to the captured image.

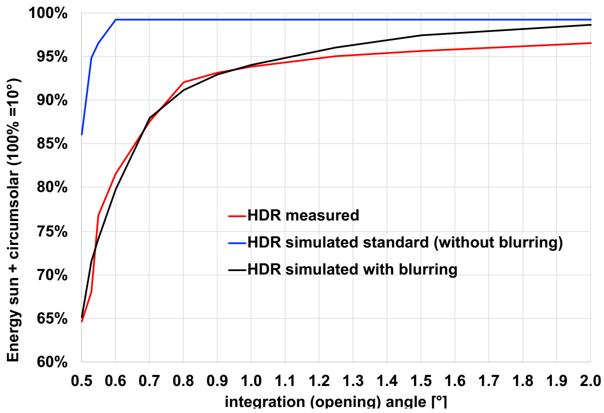

Figure 2: Energy of sun disk and circumsolar area for captured and simulated sun disk (with and without blurring) as function of the integration angle.

Model description

To re-build situations that can occur in open-plan offices, we used a wide-sized shoe-box model in the dimensions of 10m x 5m x 3m (width x depth x height), see figure 3. The simulated room is lit only from one side, the other walls are opaque (Reflection value: ρ=0.7, purely diffuse). The floor and ceiling were modelled with typical reflectance values, for Lambertian (purely diffuse) reflection: ρ_{floor}=0.2; $\rho_{ceiling}$=0.7.

The transparent façade was simplified using 2 horizontally divided panes of EC-glass without any frame in order to avoid any local shading effects. The lower pane (height 1.2m) was kept to τ_{vis}=0.2 for all timesteps. We used this height and constant transmittance value for the lower pane in order to achieve a reasonable amount of daylight while avoiding to increase the vertical illuminance as much that it contributes significantly to the saturation term of the DGP. Although, we don't consider this "control strategy" of the lower pane as optimal for a building in terms of adequate solar control and daylight provision for deeper spaces, we found this a reasonable compromise for this study to balance daylight availability, saturation and contrast glare effects. Further investigations of optimal control strategies for EC facades are out of the scope of this study.

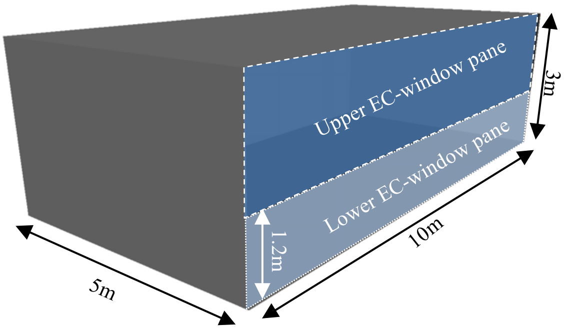

Figure 3: Visualization and dimensions of the room

Viewpoints and viewing directions

We simulated 6 viewpoints in total as two rows with 1, 2 and 3 m distance to the transparent façade and a distance of 1m each from the side wall (see illustration figure 4).

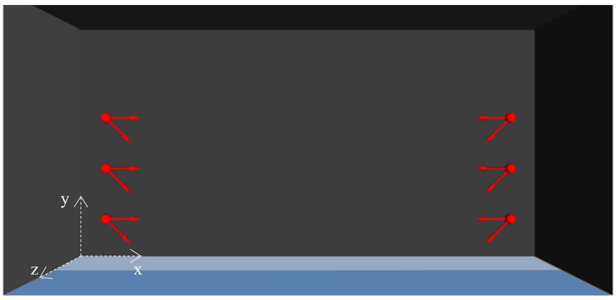

Figure 4: Top (perspective) view inside the shoebox: Visualization of the viewpoints and viewing directions.

We also simulated 2 different viewing directions: 1) parallel to the façade (labelled "P" following the naming in (Jain et al., 2022), with the sun present in the peripheral field of view) and 2) 45° from the façade (labelled "C" and mimicking a critical viewing direction in terms of increasing the glare risk with sun more frequently visible around the centre of the field of view).

We want to emphasize that the critical viewing direction "C" does not follow office layout recommendations and we also do not recommend such viewing directions. However, applying flexible office design options can lead to such situations and we think it is important to characterize the glare situations for such layouts as well.

Simulation variants

We conducted the simulations for three different locations in Europe to investigate the influence of latitude on glare classification:

Stockholm (59.35N, 18.07E), Frankfurt (50.03N, 8.52E) and Rome (41.90N, 12.48E). We used the *.wea* weather files provided by Climate.OneBuilding.Org, ids: Stockholm.024850, Frankfurt.AP.106370, Rome.Central.162380).

Our simulations include four different orientations of EC façade: South (S), South-West (SW), West (W) and North-West (NW). These orientations are selected to consider critical sun positions in terms of glare at the chosen locations.

For the upper window, we simulated 15 different tint levels, that were each kept constant throughout the entire year of simulation. This setting of the glazing transmittance does not correspond to a real control strategy of the EC-facade of course. In this study, we focused instead on determining the tint level needed to provide sufficient glare protection – for this goal a fixed transmittance level setting throughout the year is appropriate. We simulated following transmittance levels of τ_{vis}:

0.1%, 0.25%, 0.5%, 0.75%, 1%, 1.25%, 1.5%, 2%, 3%, 4%, 5%, 6%, 10%, 15% and 20%.

In total, 360 annual simulation runs were conducted (3 locations x 4 orientations x 2 viewing directions x 15 transmittance levels, the 6 viewpoints were calculated within one simulation run).

The 95-percentile DGP values are determined for each viewpoint and simulation variant separately. Out of the two viewpoints located at the same distance from the façade, the higher percentile value is reported in this study (reporting therefore the more critical position out of the two with same distance). The applied method, models and locations corresponds to the procedure that was applied deriving the tables E.7 and E.8 of the appendix of EN17037, the main author of this paper was also involved in the development of the standard.

Results

Influence of orientation and viewing direction

The figures 5-7 visualize the annual 95-percentile values of DGP as function of the glazing transmittance for the three locations, four orientations and two viewing directions (all curves are for a viewing position in 1m distance of the façade). The three glare protection categories of EN17037 are highlighted with a coloured background (minimum=orange (DGP=0.45), medium=yellow (DGP=0.40) and high=green (DGP=0.35)). For the Stockholm and Frankfurt locations, the different orientations have only little impact on the annual glare occurrence for the less critical parallel viewing direction. For the diagonal viewing direction, however, a tendency towards higher values for the West and South-West orientations can be observed for all locations. For all locations and both viewing directions, we can also see that the curves of South and West orientation are either higher or similar than the other two orientations: this means those two orientations are the most important ones to consider for glare evaluations without missing important glare occurrences. As expected, the curves associated to critical viewing direction are significantly higher than the curves for the parallel viewing direction.

The colour scale of the background of figure 5-11 indicates the glare protection class according to EN17037:

high glare protection medium glare protection

minimum glare protection no glare protection

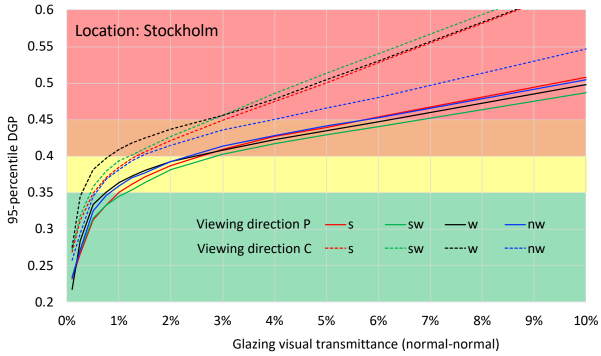

Figure 5: 95-percentile DGP as function of the glazing transmittance for Stockholm and for different orientations (s=South, sw=South-West, w=West, nw=North-West) and viewing directions (P=parallel view, C=critical view (45° towards façade)).

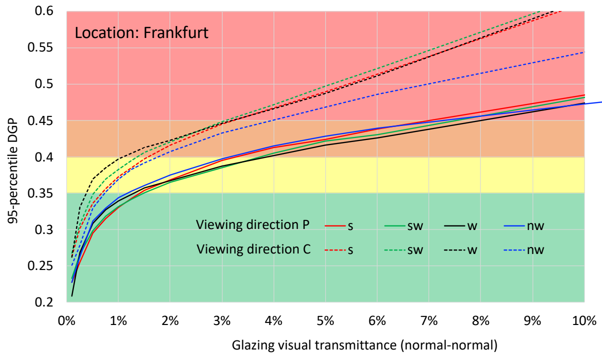

Figure 6: 95-percentile DGP as function of the glazing transmittance for Frankfurt and for different orientations (s=South, sw=South-West, w=West, nw=North-West) and viewing directions (P=parallel view, C=critical view (45° towards façade))

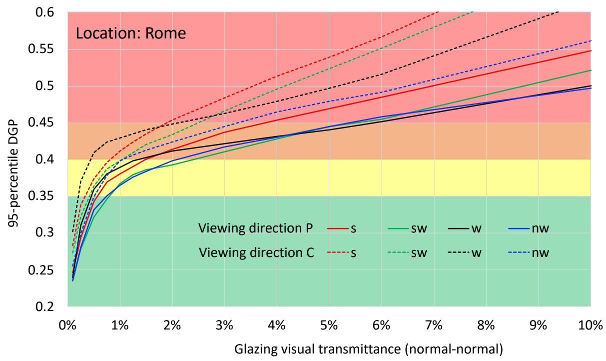

Figure 7: 95-percentile DGP as function of the glazing transmittance for Rome and for different orientations (s=South, sw=South-West, w=West, nw=North-West) and viewing directions (P=parallel view, C=critical view (45° towards façade)).

Influence of observer distance

Figures 8-11 show the impact of observer distance to the façade on the annual glare occurrence for South and West orientations in Frankfurt and Rome. For this evaluation we needed to reduce the cases to be compared. We kept the two extreme climates (omitting Stockholm) and two main orientations (omitting South-West and North-West). From 0 up until around 3% transmittance, the curves are mainly driven by the geometrical configuration influencing how often the sun disk is potentially visible by the observer. As a result, the curves for 1m and 2m are lying very close to each other for all cases. For a viewing position 3m from the window, we can observe lower values, which is caused by a reduced view to the sky due to geometry.

For transmittance levels higher than 3%, the saturation term in the DGP equation gets more influence and therefore the annual glare occurrence depends significantly on the induced vertical illuminance: deeper room locations experience less glare and the curves drift away from each other for high transmittance levels.

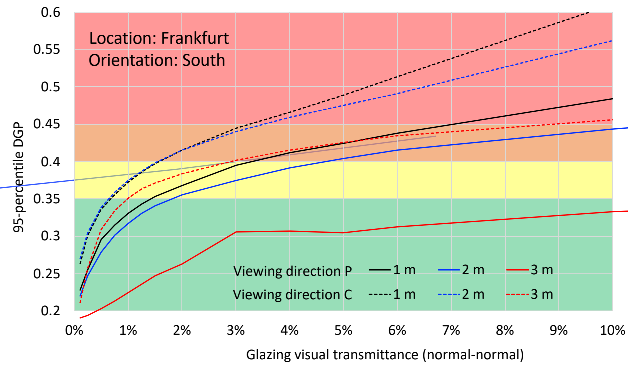

Figure 8: 95-percentile DGP as function of the glazing transmittance for Frankfurt (South orientation) and different façade distances

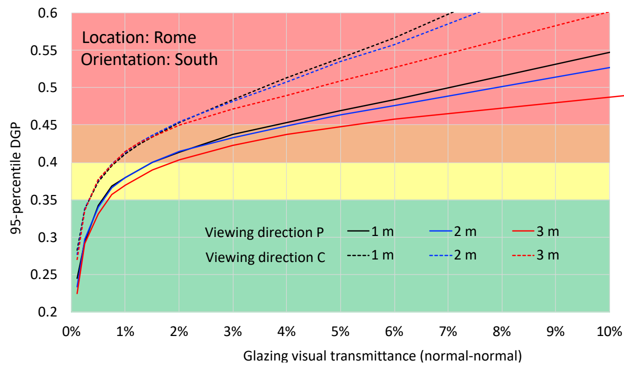

Figure 9: 95-percentile DGP as function of the glazing transmittance for Rome (South orientation) and different façade distances

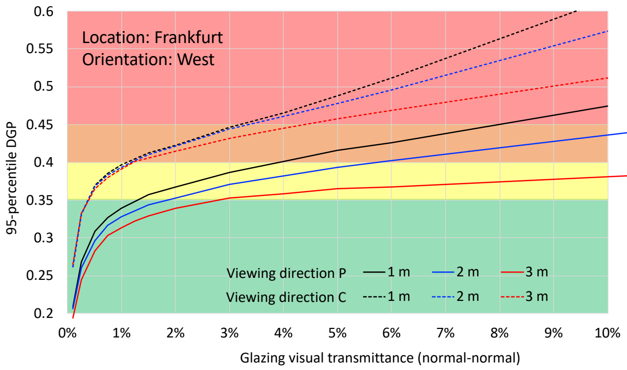

Figure 10: 95-percentile DGP as function of the glazing transmittance for Frankfurt (West orientation) and different façade distances

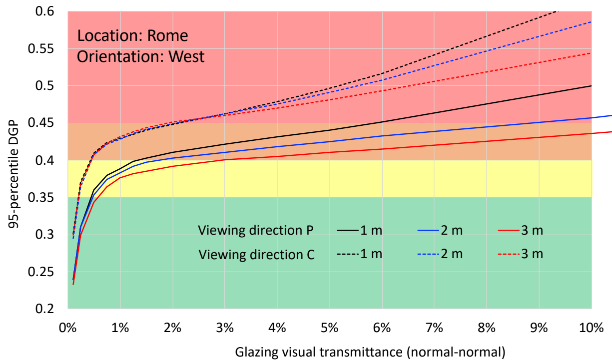

Figure 11: 95-percentile DGP as function of the glazing transmittance for Rome (West orientation) and different façade distances

Influence of latitude/climate

As can be seen in Figure 12 and 13, the annual glare-behaviour of the three climates differ significantly – with Rome showing highest glare risks, followed by Stockholm and Frankfurt having the lowest glare risk amongst the three climates.

This ranking could be expected considering the sunshine hours of the three locations (Rome: 3740h, Stockholm 2187h and Frankfurt 1748h, calculated from the weather files accounting for sunshine hours when the direct solar irradiance exceeds 120 W/m² (WMO 2018)).

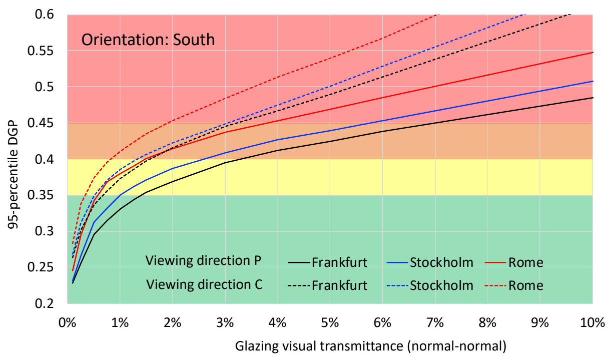

Figure 12: 95-percentile DGP as function of the glazing transmittance for different climates and two viewing directions. All values for South orientations and 1m distance to the façade.

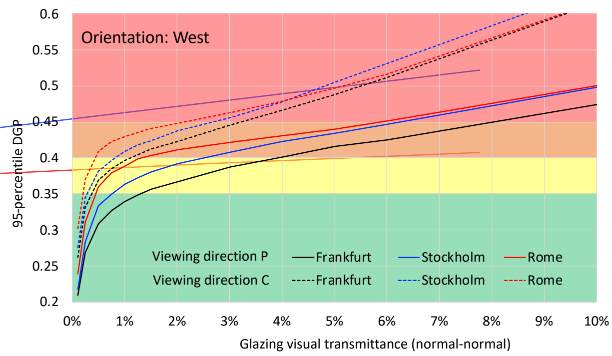

Figure 13: 95-percentile DGP as function of the glazing transmittance for different climates and two viewing directions. All values for West orientations and 1m distance to the façade.

Discussion

The results suggest that for the parallel viewing direction (that is usually recommended) a transmittance level of 1% is sufficient to achieve the highest glare protection classification according to EN17037 for Stockholm and Frankfurt. For Rome a transmittance level of 0.5% would be need to achieve the highest glare protection classification.

For the critical, diagonal viewing direction, the behaviour is similar except that one class lower glare protection is reached for the same transmittance level (1% for Frankfurt and Stockholm, 0.5% for Rome, medium glare protection is then reached, EN17037).

To reach the minimum glare protection category according to EN17037 (DGP 95percentile < 0.45), a transmittance level of 4% is sufficient for the parallel viewing direction and 2% for the critical viewing direction – independent on climate and orientation.

These results emphasize how important it is to investigate glare behaviour on annual basis and not just for some selected, critical cases. While the simulation model is able to reproduce the findings from Jain et. al 2022 quite well for critical sun positions, the annual results reveal that it strongly depends on the climate how often these critical situations occur and if a certain transmittance level of the glazing system is sufficient to fulfil the criteria given by EN17037.

Comparing the detailed results with tables E.7 and E.8 (corrigendum from 2021), one can see deviations in the calculated 95-percentiles of the DGP values (tables 1,2).

These deviations are caused by three influence factors:

1. The calculations for the EN17037 were conducted without any sun-blurring, which results in higher DGP values for the same boundary conditions.
2. For the calculations for the EN17037, the entire window pane was dimmed, whereas for the simulations in this study, parts of the window were in maximum bleached state in order to provide sufficient daylight. A complete dimming

causes a very low E_v for low switching levels, which impacts the contrast term of the DGP equation by increasing the DGP value compared to a more reasonable E_v.

3. The simulations for the EN17037 used the default mode of *evalglare* (version 2.04) applying a so called "low-light-correction" (Wienold 2012), which decreases the DGP value for E_v values lower than 500lux. That causes a significant underprediction of the DGP value for very low switching levels (1% or lower).

These three influence factors lead to important deviations between the values calculated for this study (which we see as state-of-the-art results) and the tables E.7 and E.8 of the EN17037. This finding suggests that an update of the tables in the standard will be necessary for the next revision.

Table 1: Comparison between EN17037 and this study of calculated 95percentile DGP values between 08h-18h for Frankfurt, parallel viewing direction and selected transmittance values. The used window size in this study corresponds to the large window size in EN17037.

LOCATION: FRANKFURT (SUNSHINEZONE L ACCORDING TO EN17037) VIEWING DIRECTION: PARALLEL TO FACADE									
		Orientation South				Orientation West			
Distance to facade		τ_{vis} 1%	τ_{vis} 2%	τ_{vis} 3%	τ_{vis} 5%	τ_{vis} 1%	τ_{vis} 2%	τ_{vis} 3%	τ_{vis} 5%
1m	EN17037	<0.2	0.42	0.46	0.51	<0.2	0.43	0.47	0.51
	This study	0.33	0.37	0.39	0.42	0.34	0.37	0.39	0.42
2m	EN17037	<0.2	0.22	0.40	0.47	<0.2	0.36	0.45	0.49
	This study	0.32	0.36	0.37	0.40	0.33	0.35	0.37	0.39
3m	EN17037	<0.2	<0.2	<0.2	0.31	<0.2	<0.2	0.25	0.44
	This study	0.22	0.26	0.31	0.30	0.31	0.34	0.35	0.36

Table 2: Comparison between EN17037 and this study of calculated 95percentile DGP values between 08h-18h for Rome, parallel viewing direction and selected transmittance values. The used window size in this study corresponds to the large window size in EN17037.

LOCATION: ROME (SUNSHINEZONE H ACCORDING TO EN17037) VIEWING DIRECTION: PARALLEL TO FACADE									
		Orientation South				Orientation West			
Distance to facade		τ_{vis} 1%	τ_{vis} 2%	τ_{vis} 3%	τ_{vis} 5%	τ_{vis} 1%	τ_{vis} 2%	τ_{vis} 3%	τ_{vis} 5%
1m	EN17037	0.24	0.47	0.50	0.50	0.23	0.47	0.50	0.53
	This study	0.38	0.41	0.44	0.47	0.39	0.41	0.42	0.44
2m	EN17037	<0.2	0.45	0.49	0.51	<0.2	0.43	0.49	0.52
	This study	0.38	0.41	0.46	0.46	0.38	0.40	0.41	0.42
3m	EN17037	<0.2	0.32	0.46	0.50	<0.2	0.33	0.47	0.50
	This study	0.37	0.40	0.45	0.45	0.38	0.39	0.40	0.41

Another interesting result is that the glare occurrence for the three climates are so different. To further explain this result, one has to remember the contrast term in the DGP equation, which is proportional to $L^2 \cdot \omega/(E_v^{1.87} \cdot P^2)$ with L: luminance, w: solid angle, E_v: vertical illuminance at eye level; P: Position index. While the solid angle for the glare source (=visible sun disk) is the same for all climates and independent of time of the day/year, the sun position and therefore the Position index is different between the different locations. For the 95-percentile DGP value, what matters the most is therefore how often the sun-disk is visible throughout the year (and between 8h-18h), and how often sun-luminance is high while the position index is low. We defined the sun luminance as "high", using the 25-percentile of the sun disk luminance in the EC-experiment (Jain et. al 2022) to $6.25 \cdot 10^8$ cd/m^2 (which is around 25% of the maximum possible, extraterrestrial luminance of the sun of $2.43 \cdot 10^9$ cd/m^2 as seen from earth). We define a "low position index" for values 1-4, resulting in a maximum "reduction" of the contrast term by around 1.5 orders of magnitude (P=4 means to divide by 16 in the contrast term $\sim log\ \frac{L^2\omega}{E_v^{1.87}P^2}$)

With these definitions, we calculated the number of hours per year when the sun is visible during 08h-18h and strong enough (exceeding luminance threshold and below Position index threshold) to cause glare for the West orientation and the critical viewing direction. We found for Stockholm 158h, for Rome 191h and for Frankfurt 126h per year critical for glare.

In the following figures 14-16, the representations of position index and the temporal occurrence confirm that for Frankfurt, significantly less hours of critical sun conditions occur than for the other two climates.

Although the sunshine hours for the climates show a similar trend, we assume that considering only critical sun conditions (high intensity and low position index) for a climate-classification is the more accurate approach since it uses only the relevant data. This should be investigated further.

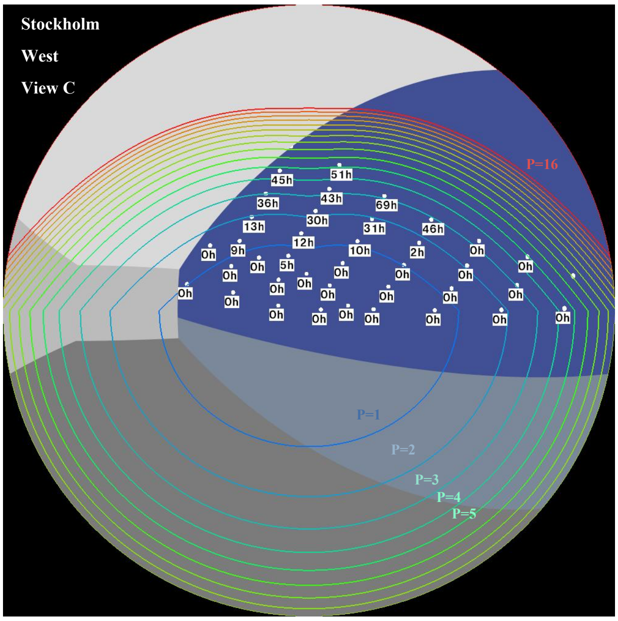

Figure 14: Visualization of visible sun position (little white dots) for the critical viewing direction C, number of critical hours between 8-18 where the sun luminance is > $6.25 \cdot 10^8$ cd/m^2 and the position index as isolines for Stockholm and West-Orientation.

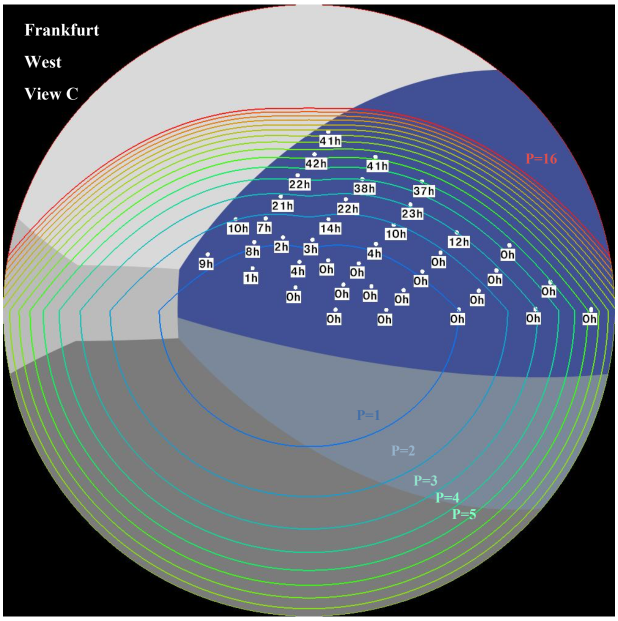

Figure 15: Visualization of visible sun position (little white dots) for the critical viewing direction C, number of critical hours between 8-18 where the sun luminance is > 6.25·10⁸ cd/m² and the position index as isolines for Frankfurt and West-Orientation.

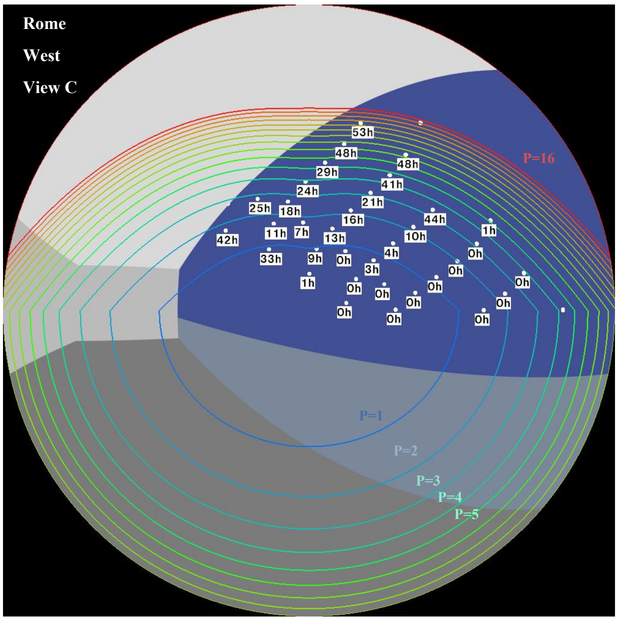

Figure 16: Visualization of visible sun position (little white dots) for the critical viewing direction C, number of critical hours between 8-18 where the sun luminance is > $6.25{\cdot}10^8$ cd/m² and the position index as isolines for Rome and West-Orientation.

Limitations

Current findings (Wienold & Jain 2021) suggest, that existing glare metrics like DGP reproduce discomfort perception of people reasonably well for blue tinting EC glazing, but also suggest that neutrally tinted glazing have lesser glare impact than the blue tinting ones. For that reason, the findings presented in this study are valid for blue tinting glazing and might differ if a prediction model considering colour effects on glare is available.

All findings are impacted by the peak extraction algorithm and threshold, applied by *evalglare*. Applying a lower threshold or defining a fixed cone around the sun direction for the glare source could lead to a decrease of the DGP value due to the $L^2{\cdot}\omega$ proportionality of the contrast term of most glare equations incl. DGP. The existing default threshold for peak extraction of 50kcd/m² was a reasonable setting for the development data of the DGP, but no study exists yet showing that this value is also the “right” setting for situations when the sun-disk is visible. The application of a gradient-driven peak extraction algorithm might be a better solution to extract a peak than using a fixed threshold, that changes size when having different tinting levels. Applying different algorithms to data with a visible sun disk will probably reduce the DGP values and therefore better reproduce the thresholds found for such cases in user studies (Jain et al. 2022).

Conclusion

This study has shown that existing EC-glazing systems able to switch to transmittance levels of 1% can mitigate glare throughout the year reasonably well for typical office situations (viewing direction parallel to the window) in mid and northern European climates.

For sunny climates as Rome (and typical office situations), a 1% transmittance level reaches the medium glare protection category according to EN17037 for all orientations.

For a critical viewing direction (which is not a recommended desk position), the usage of 1% transmittance is typically enough to reach the medium glare protection level of the EN17037 in mid and northern European climates. For the sunny climate the usage of 1% transmittance level leads to fulfil the minimum glare protection level.

The study also revealed that tables E.7 and E.8 of EN17037 with pre-calculated 95-percentile DGP values should be updated using state-of-the-art methods. As shown in tables 1 and 2, we found higher glare thresholds for parallel viewing direction compared to EN17037 for VLT=1%. Whereas we found lower glare thresholds for VLT>=2% in this study compared to EN17037.

The deviations in values are significant and are caused by the method applied for deriving the EN17037 values and result from a combination of the following factors: a) non-sun blurring b) full tinting of all glass panes causing low adaptation levels c) using default low-light correction function in *evalglare*.

Another important conclusion is the importance of conducting annual simulation to investigate the performance of glare protection systems. Considering only critical conditions might lead to different conclusions and potentially to an “oversizing” of shading systems. However, considering the large variability between human occupants in terms of glare perception, the application of user-adjustable control algorithms for a dynamic shading system to adjust to individual needs will definitely increase the acceptability – independently of the technology (e.g. EC, fabric or Venetian blinds) used for glare protection.

Acknowledgement

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A critical analysis of questionnaire items for discomfort glare studies in daylit spaces

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Abstract

When studying discomfort glare, researchers tend to rely on a single questionnaire item to obtain user evaluations. It is still unknown whether the type of glare questionnaire item influences the distribution of user responses and if this leads to inconsistencies in findings between studies that use different questionnaire items. The objective of this study is to determine whether different glare questionnaire items capture similar distributions of user discomfort from glare in rating-type experiments conducted in daylit environments. We carried out a comparison study by selecting which questionnaire items and tested them in three independent user studies of varied lighting conditions and glare stimuli. We compared the resulting outputs across questionnaire items with 540 data points from 149 participants. The outputs of ordinal questionnaire items showed high correlations ($0.68 < \rho < 0.85$) and internal reliability ($\alpha = 0.93$) and pointed to the same latent construct. Binary questionnaire items corresponded to different thresholds of glare but still showed good correlations to ordinal items. The validity of the latent construct was validated with responses to an open-ended question. These findings show that the tested questionnaire items can be used for category rating-type discomfort glare evaluations and indeed point to the same construct.

1 Introduction

In the fields of health, social and behavioral research, scales are "collections of items combined into a composite score intended to reveal levels of theoretical variables not readily observable by direct means"[1]. They represent one or more latent constructs, allowing us to assess and capture a behavior, an action, or a feeling that cannot be captured in a single variable or measured by other direct means[2]. Scales are typically composed of multiple questionnaire items that measure an underlying latent construct and protect against the influence of culture, biases, and item order, resulting in higher accuracy in scientific investigations[3,4]. Questionnaire items typically include a question and a response scale of response items, and sometimes include definitions of keywords to aid comprehension.

The avoidance of discomfort glare is one of the key factors to consider when designing indoor spaces with high comfort levels for occupants, which is also acknowledged in existing standards (EN12464, EN17037)[5,6]. The International Commission on Illumination (CIE) defines discomfort glare as “condition of vision in which there is discomfort without necessarily impairing the vision of objects”.[7] In discomfort glare research whether conducted in controlled laboratory settings or field studies, researchers typically collect subjective responses from participants using questionnaire items, which include the question, the response scale, and the format in which they are presented, with or without definitions.[8] For discomfort glare, no calibrated scale consisting of a collection of questionnaire items for discomfort glare has been developed so far. When studying the extent of discomfort glare effects, researchers tend to rely on a single questionnaire item for user evaluations of the degree of discomfort glare perceived as the main underlying latent construct. There have been numerous suggestions and criticisms about the wording of the question, the response scale and its items, the format in which they are presented, and whether accompanying definitions are included[8–11]. It is still unknown whether the type of glare questionnaire item chosen for user studies influences the response distribution due to a lack of user studies to investigate this. If there is an influence, the results of studies that use different questionnaire items may differ.

Therefore, in this paper, we aim to determine whether a selection of glare questionnaire items captures similar distributions of user discomfort from glare as resulting outputs in rating-type experiments conducted in daylit environments. To that end, a comparison study is carried out, which entails selecting which questionnaire items to test and then testing them in a randomized order in glare evaluations in three user studies of varied lighting conditions, and finally comparing their resulting outputs across questionnaire items (a total of 540 data points from 149 participants). The findings are then presented using descriptive analysis methods and psychometric statistics, as well as tests of association, reliability, and dimensionality. The latent construct that the tested questionnaire items solicit is also checked for validity.

2 Background

Numerous critiques of some of the most commonly used questionnaire items in various glare studies have been published, and some previous literature has offered several pointers such as the comprehensibility and ordering of verbal descriptors in the response scale used[9,10]. The critiques emphasized the inconsistencies of glare questionnaire items, reflected on whether meaningful results can be obtained through questionnaire items, and discussed their advantages and disadvantages. In ideal cases, questionnaire items should meet a few key requirements, such as being easily understood by the participant and avoiding memory retrieval, which means asking the participant about a previous experience rather than the current situation they are exposed to[11]. It should only ask one question at a time, and should not mix concepts such as satisfaction, acceptance, and discomfort within the same questionnaire item, and response items should also be clear and have straightforward descriptors. Some researchers also suggested that a “no glare” or null option be included in the response items[12,13] so that participants are not forced to report glare when they do not perceive any. However, these pointers for designing glare questionnaires, in general, may sometimes only apply to category-rating test procedures but not adjustment-type procedures which require the active interaction of the participant with the visual scene[8]. Category-rating test procedures typically expose participants to one scene or stimuli at a time and ask participants to rate pre-defined variables through questionnaire items, while adjustment-type procedures usually expose participants to a starting scene or stimuli and ask them to adjust the parameters of the stimuli to fit described levels of stimuli such as the multiple-criterion method.

Other suggestions include giving the participant a layman's definition of the key variable in question, presenting response items in a logical and relevant order, and including a “don’t know” option to capture participants who do not understand or know what they are perceiving[10]. A balanced number of response items on each side of the neutral point should also be maintained for bipolar or semantic differential scales[10,14,15]. If numbers are used in addition to verbal descriptors as response items, they should correspond in increasing order of intensity, for example, "0" should correspond to "Not at all" and "10" should correspond to "Very much" on a scale of 0 to 10[16]. Additionally, instead of asking about the degree of discomfort from glare, some researchers proposed using a positively worded statement in conjunction with a Likert agreement scale to pose the question more optimistically[12]. Other suggestions include a fixed equal distance between response items, language consistency, and a greater number of response items on the scale than glare stimuli levels for sufficient resolution[17]. A recent proposal for questionnaire standardization is a two-step skip-sequencing method for evaluating discomfort from glare[11], suggesting first asking the participant if they are experiencing discomfort from glare. If the participant answers yes, then they are asked a second question on a 6-point scale labelled 1 (Very small amount) to 6 (Very large amount). If the participant answers no, the second question will be skipped.

However, these critiques on questionnaire items have not been studied qualitatively so far, and multiple variations of questionnaire item types have been used to solicit evaluations on the degree of glare in past user studies, from which discomfort glare prediction models have been developed. The multiple-criterion method for subjective glare appraisals in adjustment-type experiment procedure was first proposed by Hopkinson[18] and participants were asked to adjust a lighting variable based on a criterion of discomfort glare on the multiple criterion scale[19]. The 4-point ordinal multiple criterion scale originally published in 1940 consisted of four degrees of discomfort glare as follows: “A: Just intolerable, B: Just uncomfortable, C: Satisfactory, and D: Just not perceptible”. Petherbridge and Hopkinson developed the British Research Station (BRS) glare index[20] to describe discomfort glare from electric lighting fittings in 1950, using a semantic variation of this response scale with C and D changed to “C: Just acceptable, D: Just imperceptible”. In hindsight, MacGowan questioned if these response items, which may not seem as easily comprehensible might have been better understood at the time they were proposed[21]. In 1960, Hopkinson and Bradley developed the ‘Cornell formula’ which used another semantic variation of the scale with criterion D changed to “D: Just perceptible” to study discomfort glare from large windows simulated by electric lighting apparatus, using adjustment procedures[22,23]. In 1962, the Illuminating Engineering Society (IES) glare index was established by modifying the BRS glare index[24]. For adjustment-type test procedures, Kent *et al.* found significant differences in the luminances adjusted by the participants when criteria on the multiple criterion scale were presented in ascending order, compared to when the presentation order of the criteria was randomized[25].

Using a category-rating test procedure, Chauvel et al. modified the ‘Cornell formula’ through user assessments for discomfort glare studies in daylit buildings, asking observers to assess the level of discomfort in the scene presented to them[26]. Their study used the multiple criterion scale in the England study and a categorical five-point scale in the France study: “1 – not uncomfortable, 2 – slightly uncomfortable, 3 – rather uncomfortable, 4 – very uncomfortable, and 5 – extremely uncomfortable"[23]. Iwata et al. developed the Glare Sensation Vote (GSV) model in 1992 in daylight conditions with user assessment procedures using the 4-point multiple-criterion scale similar to Hopkinson and Bradley[27]. In 1995, the International Commission on Illumination (CIE) proposed the Unified Glare Rating (UGR)[28] where Sorensen developed UGR[29] using Petherbridge and Hopkinson's dataset. The UGR formula incorporated the IES glare index as well as mathematical corrections proposed by Einhorn for the CIE glare index (CGI)[30,31].

Fisekis *et al.* used a 7-point multiple criterion scale similar to the "Stage 2" of the multiple criterion scale without the "Just intolerable" criterion to modify DGI and UGR resulting in the modified Daylight Glare Index (DGI_{mod}) and the experimental Unified Glare Rating (UGR_{exp})[32], adapted for daylight glare from windows. Wienold and Christoffersen developed the Daylight Glare Probability (DGP) in 2006[33] through user studies using a 4-point response scale with "Imperceptible, Noticeable, Disturbing, Intolerable" introduced by Osterhaus and Bailey[34] which is also similar to Hopkinson's 4-point multiple criterion scale. Here, the word "just" was also omitted in the response scale items as Hopkinson's multiple criterion scale was originally meant for adjustment procedures where the borderlines of comfort and discomfort were pertinent. In 2014, Hirning *et al.* adapted UGR for daylight conditions in deep open-plan offices, resulting in Unified Glare Probability (UGP)[35]. He collected glare responses using a glare indication diagram, which asks participants to indicate on a diagram where a glare source, if any, is in their field of view. Any marking on the glare indication diagram is interpreted as indicating that the participant experienced uncomfortable glare in that scene.

As described, we can observe that beyond the type of test procedure used (adjustment, or category-rating), there have been multiple variations to the questionnaire types and the response scales used by researchers when studying discomfort glare. An overview of variations of questionnaire items that have been used in user studies that culminated in glare model development can be found in the supplementary material. It is not yet known whether the usage of different questionnaire items in rating-type experiments may produce varying glare response results and could therefore also bias results, such as in the development of discomfort glare models for example.

3 Methodology

As a step to study the reliability between questionnaire items, we want to investigate whether the choice of questionnaire items for user studies affects the distribution of glare responses from participants. To develop the methodology, we referred to best practices recommended in the psychometry field for scale development[36]. However, in this case, instead of scale development, we are looking to compare the outputs of several glare questionnaire items. Hence, we omit factor extraction since we are only interested in one dimension (or factor) which is the extent of discomfort glare experienced if any. As a result, we chose four steps for the relevance of comparing questionnaire items - we use a process of item generation, survey administration, and tests of dimensionality and reliability in our workflow as shown in Figure 1.

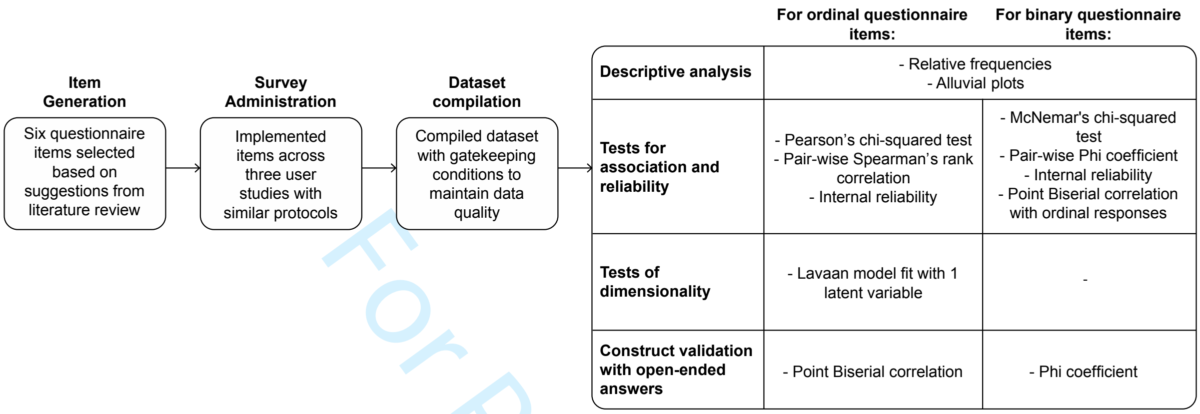

Figure 1 Methodological workflow to analyze questionnaire items for discomfort glare studies.

To execute this four-step process toward comparing the output of questionnaire items, we tested the selected questionnaire items across three independent user studies that evaluated discomfort glare from daylight each with unique research objectives and therefore covering a wide range of glare stimuli from daylight. These three user studies result in a dataset that covers a wide range of vertical illuminances from 216 to 7300 lux. Therefore, to answer this question, we administered six chosen questionnaire items on discomfort glare perception in English in three parallel user studies conducted by the authors in indoor daylit environments and using similar experimental protocols (540 data points from 149 participants). This is a collaborative study in which we decide on the relevant questionnaire items we want to compare and coordinated to administer them simultaneously across three user studies. In the following sections, we go into detail about the questionnaire items selected for comparison, the experimental protocol for survey administration, and data compilation. Finally, a construct validation of the questionnaire outputs is carried out using open-ended answers to a general question that was asked to the participants before all six questionnaires were first seen by them.

a. Selecting questionnaire items

This section describes how the questionnaire items were generated and assessed for viability before being administered in this comparison study. To cover a wide range of questionnaire types used in daylight glare research and related indoor environmental quality (IEQ) studies, "Binary-YesNo", "OsterhausBailey-4point", "Likert-4point", "Interval-0-10", "Comfort-agreement", and "Glare-indication-diagram" were chosen and are shown in Figure 2. These six questionnaire items were chosen for the following reasons.

First, "OsterhausBailey-4point", "Binary-YesNo" and "Glare-indication-diagram" were chosen as they are commonly used in the field [34,35,37,38], while the other three questionnaire items were chosen to add variety to the selection while being viable candidates according to the suggestions from literature. The "Glare-indication-diagram" which was not a typical questionnaire item and requires participants to mark on a diagram if they experience discomfort glare, was still included because it was used to develop a glare model from surveys in open plan offices, namely Unified Glare Probability (UGP)[35]. Similar to Hirning *et al.*, we interpreted the results of the Glare-indication-diagram by converting any marking on the diagram to "Yes" and none to "No". "Likert-4point" was chosen as it has a simple Likert format, and has easy-to-understand, incremental response items. "Interval-0-10" is an 11-point numerical scale with labels ranging from "Not at all" to "Very much" at the extremes, similar to "Likert-4point". "Comfort-agreement" was chosen to serve as a positively worded question to the selection[12]. Last, these questionnaire items were chosen specifically for applicability in rating-type studies, in which participants are exposed to a lighting condition and asked to rate their discomfort by answering a questionnaire. For example, we believe Hopkinson's questionnaire item[19] is inappropriate for our user studies because it was originally developed to be used in adjustment-type studies and not rating-type studies. For the participants to understand the definition of glare without knowing technical terms, a layman's definition of glare was derived by referencing the CIE's definition of glare[7]: “Glare is the sensation of visual discomfort caused by differences between light and dark areas, or by excessive brightness in your field of view.” This was shown to the participants alongside each questionnaire item[1].

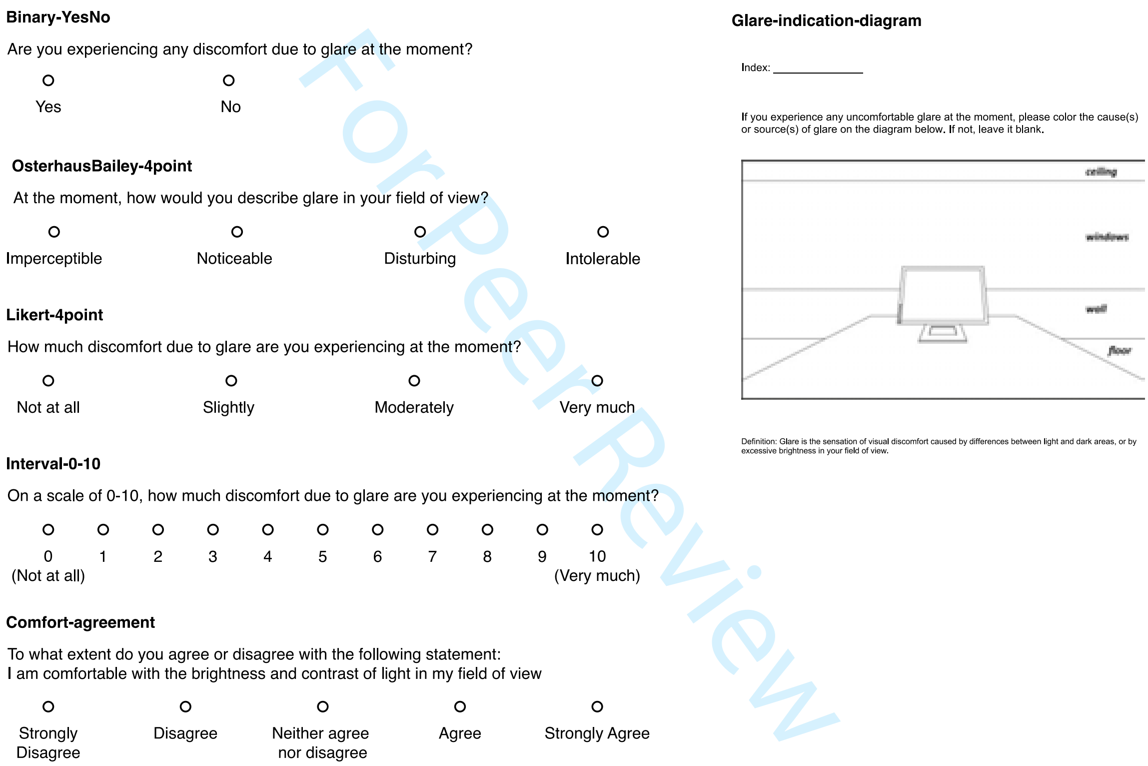

Figure 2 Six questionnaire items were selected for comparison.

Additionally, to ensure that the questionnaire items selected for this study are viable, we compare them to a compiled list of suggestions in past literature as mentioned earlier in Section II. A list of questionnaire design suggestions from previous literature in the discomfort glare field was compiled, and we compare the viability of the selected questionnaire items to the list as shown in Table 1. These suggestions were argued in the respective cited publications for more meaningful and informative glare questionnaire designs. If the pointer does not apply to the questionnaire item, it is simply not evaluated and labelled "N.A.". As can be seen, it is nearly impossible for any questionnaire item to satisfy all suggestions at the

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[1] The participants were given a layman's definition so that they could understand without knowing the meaning of terms like "luminance". The layman's definition was derived from CIE's definition of discomfort glare - "glare that causes discomfort without necessarily impairing the vision of objects" as well as glare, defined as a “condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme luminance contrasts”[39].

same time. For example, the nature of ordinal response scales is that the orders of the values are known, but the distance between them is not, and hence will not meet the requirement of "equal distance between items on response scale". Similarly, the pointer suggesting a positively phrased question can only be fulfilled if the question does not inquire about the users' perception of discomfort. As one may observe, all six questionnaire items selected fulfilled at least half of the applicable suggestions. Hence, we went ahead with administering all of them in a random order of presentation in all three user studies.

Table 1 Six glare questionnaire items were evaluated alongside a list of suggested pointers from previous literature regarding questionnaire design.

Suggestions from past literature	Reference	"Binary-YesNo"	"OsterhausBailey-4point"	"Likert-4point"	"Interval-0-10"	"Comfort-agreement"	"Glare-indication-diagram"
Comprehensible question	40	1	1	1	1	1	1
Clear descriptors on the scale	10,14	1	0	1	1	1	N.A.
No mixing of concepts	10,14,17	1	0	1	1	1	1
Include null option	12,13	1	1	1	1	1	1
Avoid memory retrieval from past experience	40	1	1	1	1	1	1
Layman's definition of key term in question	10	1	1	1	1	N.A.	1
Response items in relevant order	10	N.A.	1	1	1	1	N.A.
Include "Don't know" option	10	0	0	0	0	0	0
Balanced response items on each side of the neutral point (for bipolar/semantic differential scales)	10,14,15	N.A.	N.A.	N.A.	N.A.	1	N.A.
Correspondence between number and verbal descriptors	16	N.A.	N.A.	N.A.	1	N.A.	N.A.
Include a positively worded question	12	0	0	0	0	1	0
Equal distance between items on response scale	17	N.A.	0	0	1	0	N.A.
Language consistency (English, or validated translation)	17	1	1	1	1	1	1
Scale representing stimuli range	17	N.A.	1	1	1	1	N.A.

To check for construct validity of the questionnaire items, a generic open-ended question, Binary-Open, was asked to participants at the beginning of the questionnaire for each evaluated scene: “Is there anything about the physical environment that disturbs you at this moment? (Answer "No", if you are not disturbed by anything.)”. We processed their open-ended answers by categorizing them into two bins, Yes and No. Any mention of glare, bright sources of light caused by the sun, façade, or reflections is categorized as Yes, and No if none of these are mentioned. Only the first data point from every participant was used for this analysis, such that they would not have been exposed to glare questionnaire items before answering the open-ended question and that Binary-Open would have been presented for the first time to them. This resulted in a total of 137 data points for validating the latent construct.

b. Survey administration and data compilation

Following their selection, these six questionnaire items were implemented concurrently in three different user studies by the authors, each with a different setup but producing glare stimuli from daylight and all following a similar experimental protocol in office-like conditions. All three user studies were held in the same test facility, DEMONA (East), on the EPFL campus in Lausanne, Switzerland, between September 2020 to October 2021. DEMONA (East) is a single-room facility approximately 3 by 7 meters in dimension and has thermal room conditioning capabilities with radiative walls for heating and cooling. Their specific data collection periods are shown in Table 2. The first study[41] focused on contrast-dominant glare in low photopic ranges with a mean vertical illuminance of 759 lux, and the second focused on discomfort glare through shading fabric with contrast-dominant glare and high photopic range with a mean vertical illuminance of 1834 lux[42]. The third study[43] focused on discomfort glare with direct sun in the field of view (FOV) through low transmittance, color-neutral glazing with a mean vertical illuminance of 3129 lux. To investigate the influence of questionnaire items on glare responses, we combined the three collected sets of data into one consolidated dataset which embodied a large range of daylighting conditions where the selected questionnaire items were administered.

Table 2 Breakdown of the number of participants and data points included in each study, when they were conducted, and their corresponding ranges of vertical illuminances.

Dataset	Data collection period	Unique participants	Total data points	Vertical Illuminance range (lux)
1. User study in contrast dominant discomfort glare in dim daylit conditions[41]	September to October 2020, March to April 2021	62	234	Min: 216 lux Mean: 759 lux Max: 2080 lux Standard Deviation = 370 lux
2. User study of discomfort glare from shading fabrics[42]	December 2020 to March 2021, October 2021	32	109	Min: 260 lux Mean: 1834 lux Max: 4960 lux Standard Deviation = 1348 lux
3. User study with direct sun as a glare source (only data from color-neutral glazing are used) [44]	October 2020 to March 2021	55	200	Min: 830 lux Mean: 3128 lux Max: 7300 lux Standard Deviation = 1341 lux
	Total	149	540	

The three user studies followed a category-rating procedure, rating four luminous scenes in a randomized order. Participants were exposed to one lighting scene at each time and asked to complete a typing task for at least five minutes to allow their eyes to adjust to the lit environment. After the typing task, they were then asked to complete an on-screen survey administered by the online survey platform Alchemer. The generic open-ended question, Binary-Open, was asked to each participant first. After this, all six questionnaire items in all three studies were administered to each participant in a randomized order, in a one-question-per-page format in English along with a layman's definition of glare as mentioned earlier. To test the understanding of the semantics of the response items as-is, we did not give additional definitions or explanations of the response items on the scale to the participants, even though for example, the early implementation of the OsterhausBailey-4point questionnaire item gave time-based explanations[34].

Table 2 contains a breakdown of the three datasets and their corresponding ranges of vertical illuminances. The first study varied the luminance and size of glare sources created using different combinations of diffuse films and low-transmittance color-neutral films attached to the window. The second study varied fabric blinds with different openness factors with direct sun in the field of view, while the third study varied the luminance of the direct sun disk with color-neutral films of different low transmittances. Figure 3 shows the four scenes of each of the studies where the questionnaire items were administered. In the second study, there were a total of five scenes evaluated where the participant was asked to adjust the blinds in the fifth scene. However, we only considered the first four evaluated scenes of each user study when compiling the sets of collected data from the three user studies. There were no other critical differences in their experimental protocol other than the luminous ranges focused on by each study.

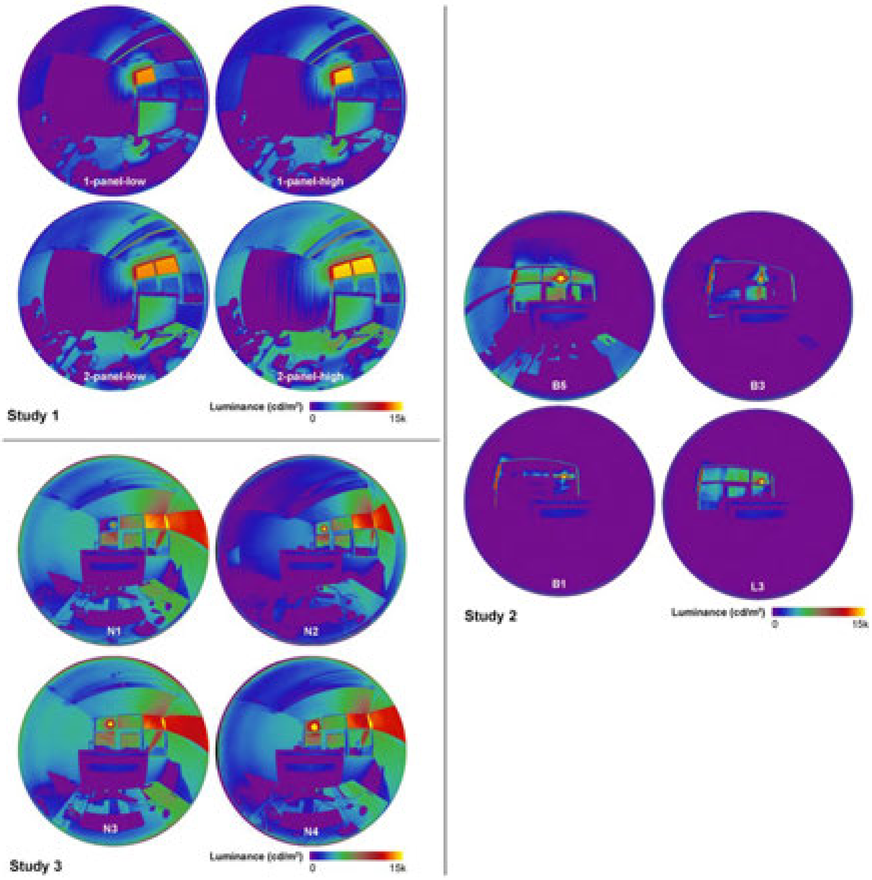


Figure 3 Example HDR images of the four scenes evaluated in each of the three studies where the questionnaire items were administered.

Participants in all three studies were also recruited such that they have at least C1 English proficiency according to the Common European Framework of Reference for Languages (CEFR), are not studying or working in the built environment sector, do not have any eye related pathologies, have normal color vision, and are between the ages of 18 and 30, and present in good health on the day of their scheduled participation in the user studies. The three user studies, in which all six questionnaire items were administered, were conducted in Lausanne, Switzerland, with no repeat participants. There were no additional recruitment criteria based on cultural background because it had previously been discovered that cultural background has no significant effect on glare perception[45].

Each data point consists of one participant's answers to all six questionnaire items to one lighting scene, which is measured using HDR images and illuminance meters, as well as weather conditions measured either by continuous vertical illuminance (E_v) measurements indoors, or global horizontal irradiance (GHI) measured outdoors[2]. We filtered the data in the following way to ensure that the lighting conditions remained stable throughout the survey

[2] The difference between these two proxies for weather stability is that the former is measured indoors from the participant's viewing direction, while the latter is measured on a rooftop of a nearby building. As a result, the former may reflect fairly accurate fluctuations of illumination in the south-facing test room, whereas the latter may be influenced by outdoor conditions such as passing clouds in the northern part of the sky.

duration so that for an evaluated scene, all six questionnaire items were answered with the fewest variations in lighting conditions due to fluctuating weather conditions.

Where continuous vertical illuminance was available in the first study (as derived from continuous captures of HDR images indoors (every 15 seconds)), we removed data points above a 25% deviation of vertical illuminance, $(E_{v,\,max} - E_{v,\,min})/(E_{v,\,mean})$ for the duration of the participant's exposure to the scene (from typing task to the end of the survey). The 25% threshold was used for gatekeeping criteria for weather stability used in the field[45,46]. For the second and third studies, we removed data points where the GHI deviated more than 25% $(GHI_{max} - GHI_{min})/(GHI_{mean})$, as measured by an on-site outdoor pyranometer (every 1 second). We exceptionally accepted a few more data points where the E_v or GHI deviation was higher than 25% during the typing task period but not during the survey response period. Using the data filtering protocol described above, 63 data points were removed, leaving 540 data points from 149 distinct participants in the compiled dataset for analysis.

4 Results

a. Descriptive analysis

In this section, we use the compiled dataset to analyze how participants responded to the six questionnaire items. Here, we ran descriptive analyses using stacked bar charts to describe the relative frequencies of each response item and paired alluvial diagrams to illustrate the flow of user responses. We chose to use alluvial plots as they represent the flow of data from one state to another, and flow lines represent the percentage of respondents, which are typically colored by the variables of the first state. We can see how participants respond to one questionnaire item after another while also describing the percentages of responses for each response item. Note that the order of the questionnaire items in the alluvial plots does not reflect the order in which they were asked to participants because the questionnaire items were presented to them in a randomized order each time.

The stacked bar chart in Figure 4 depicts how the 149 participants responded to the six questionnaire items in 540 evaluated scenes based on the compiled dataset. For the two questionnaire items with two response items, "Binary-YesNo" and "Glare-indication-diagram", 48% of participants answered “Yes” to Binary-YesNo while 65% indicated a glare source on the Glare-indication-diagram. Although both questionnaire items are binary, there is a mismatch in the distribution of results, most likely due to the latter being asked on paper rather than as an on-screen questionnaire item. On the OsterhausBailey-4point response scale, approximately 70% of participants reported noticeable glare and above, while 25% reported disturbing glare and above. The response distribution of the other questionnaire with four response items, Likert-4point, was similar, with 68% of participants reporting slight glare and above and 27% of participants reporting moderate glare and above. The Interval-0-10 questionnaire item produced a higher resolution due to its 11 response items. On the Interval-0-10 questionnaire, 28% of participants rated 6 or higher (beyond the middle point of 5). For the positively worded Comfort-agreement questionnaire, 30% disagreed that the brightness and contrast in their field of view were comfortable.

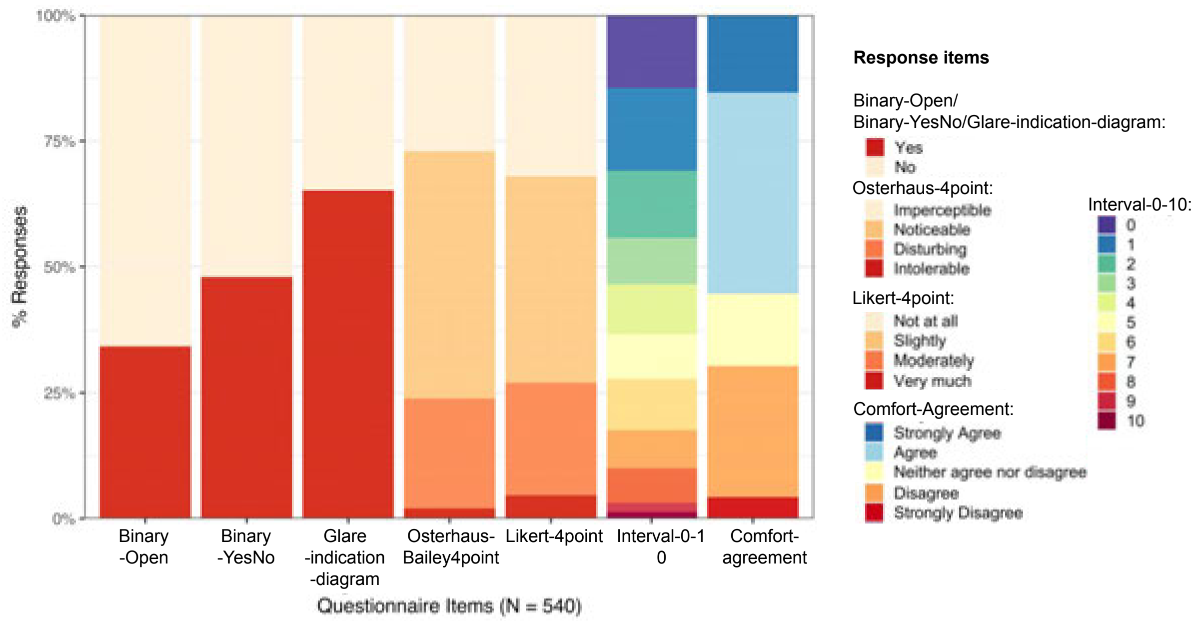


Figure 4 Stacked bar chart showing relative frequencies of responses across the six questionnaire items as well as Binary-Open, which will be used for checking for construct validity.

For the binary questionnaire items, a pairwise alluvial plot of how participants answered the Binary-YesNo question versus the Glare-indication-diagram is shown in Figure 5, revealing a difference in response distribution. A larger percentage (65.2%) of participants indicated a glare source on the Glare-indication-diagram than the percentage of participants who reported "Yes" to the Binary-YesNo (48%). The flow lines connecting "No" on the Binary-YesNo questionnaire item to "Yes" on the Glare-indication-diagram demonstrate the participants (17%) who answered "No" to the Binary-YesNo question but also indicated a glare source on the diagram. Such differences are sufficient to affect derived discomfort thresholds such as in DGP. The full set of possible pairwise alluvial plots between the six questionnaire item outputs can be found in the supplementary material. Answers from the open-ended Binary-Open (only the first responses from each participant) will be used to check for construct validity later in the analysis.

Furthermore, the percentage of participants who reported glare on the Glare-indication-diagram corresponds to the beginning of "slightly" and "noticeable" responses on the OsterhausBailey-4point and Likert-4point questionnaire items, respectively, as shown in Figure 6. Meanwhile, the positive responses on Binary-YesNo correspond to somewhere in the middle of the "slightly" and "noticeable" responses as shown in Figure 5. Although both questionnaire items have binary output, this phenomenon could imply that the answers to these two questions correspond to different levels of discomfort, with the Glare-indication-diagram corresponding to noticeable discomfort and the Binary-YesNo corresponding to somewhere between noticeable and disturbing discomfort. In other words, positive responses from Binary-YesNo refer to a higher threshold between "noticeable" and "disturbing" thresholds, while positive responses from Glare-indication-diagram refer to a lower threshold nearer to the "imperceptible" to "noticeable" threshold.

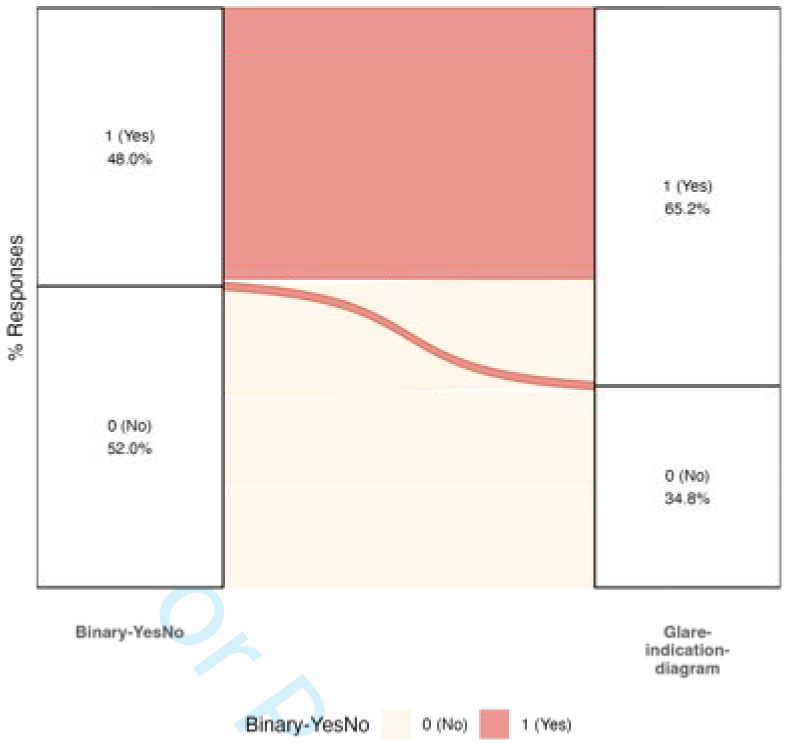
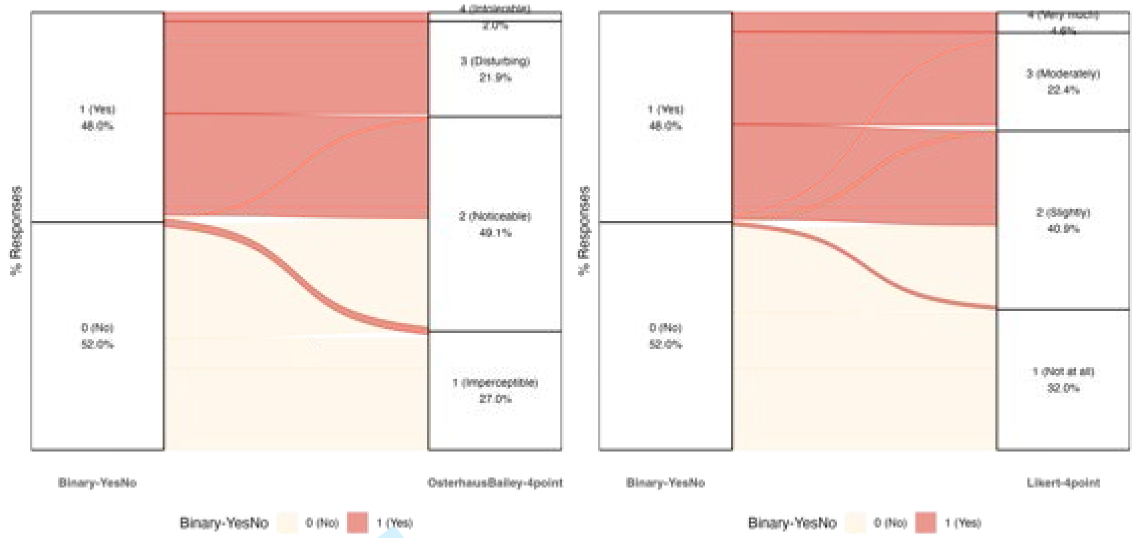


Figure 5 Pair-wise alluvial plot showing the flow of participants' responses between Binary-YesNo and Glare-indication-diagram.

Figure 6 depicts the pair-wise alluvial plots between Binary-YesNo and OsterhausBailey-4point, as well as of Binary-YesNo and Likert-4point respectively. Both questionnaire items have four response items and are compared to the binary questionnaire item distribution, Binary-YesNo. Surprisingly, participants who answered "No" to Binary-YesNo did not all answer "Imperceptible" or "Not at all" in both cases. 50% of those who answered "No" said it was "Noticeable" on the OsterhausBailey-4point, and 38% said it was "Slightly" on the Likert-4point. It can be seen that "No" in a binary questionnaire item does not always correspond to an absolute null response in other questionnaire items with a higher resolution (more than two response items). This phenomenon also occurs between Binary-YesNo and Interval-0-10 with a response scale of 11 points. Figure 7 shows the pairwise alluvial plot between them, which shows that two-thirds of the total participants who answered "No" to the binary question answered more than "0" on the Interval-0-10 response scale.



(a) Binary-YesNo and OsterhausBailey-4point (b) Binary-YesNo and Likert-4point

Figure 6 Pair-wise alluvial plots showing the flow of participants' responses between Binary-YesNo and between OsterhausBailey-4point and Binary-YesNo and Likert-4point.

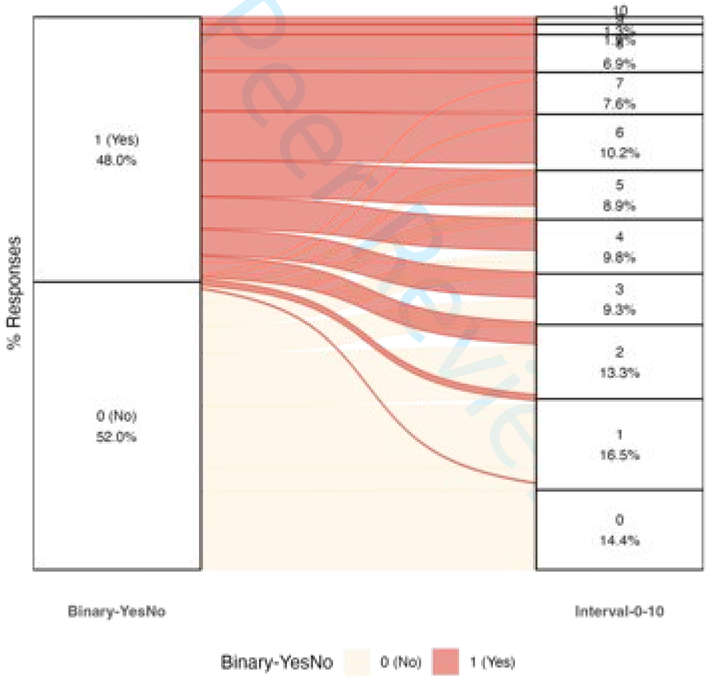


Figure 7 Pair-wise alluvial plot showing the flow of participants' responses between Binary-YesNo and Interval-0-10.

There is some indication that participants responded similarly between the two questionnaire items that contain four response items, OsterhausBailey-4point and Likert-4point. Interestingly, as shown by the orange flow lines in the pair-wise alluvial plot in Figure 8 colored by the response scale of the OsterhausBailey-4point questionnaire item, participants who answered "Noticeable" to the OsterhausBailey-4point also answered "Moderately" and "Not at all" to the Likert-4point. However, overall, this observation implies that the four response items between the two questionnaire items generally correspond to each other. In the following section, we will delve deeper into the psychometric analysis that statistically confirms this indication.

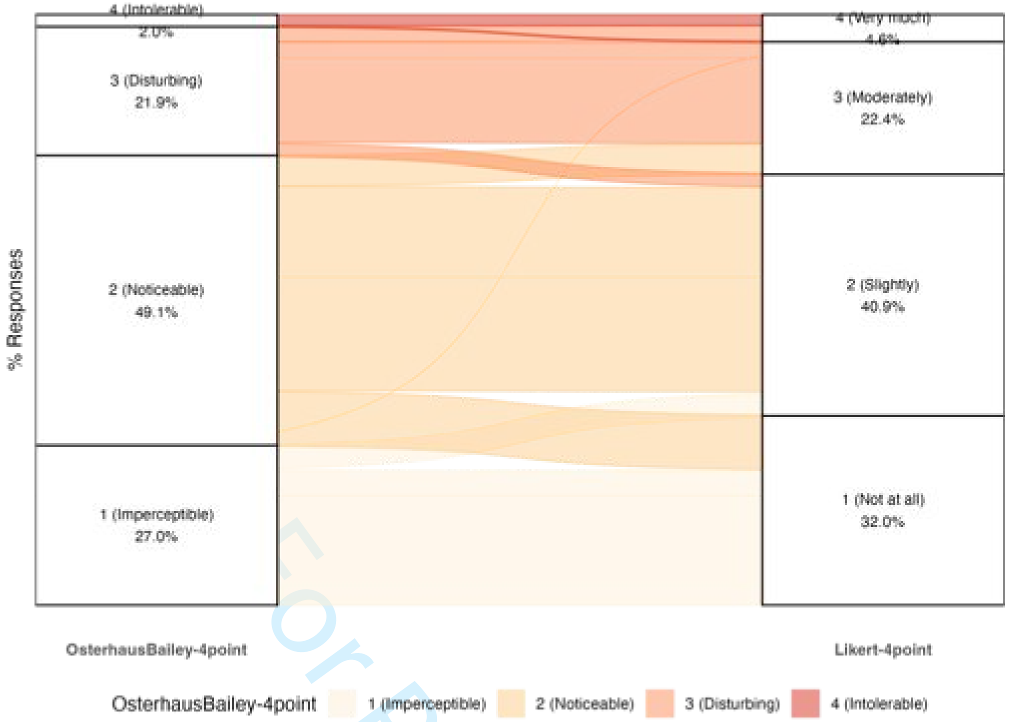


Figure 8 Pair-wise alluvial plot showing the flow of participants' responses between OsterhausBailey-4point and Likert-4point.

b. Psychometric analysis

To confirm the results of the descriptive analyses in the previous section, we will use a selection of statistical methods to determine if there is sufficient evidence that the response outputs of the questionnaire items are contradictory.

The following statistical tests were performed to test for association and reliability for the four ordinal questionnaire items with more than two response items, namely "OsterhausBailey-4point", "Likert-4point", "Interval-0-10" and "Comfort-agreement". The Pearson chi-squared test was conducted to test the relationship between the outputs of the questionnaire items. Spearman rank correlation was then calculated to check the correlational strength between the ordinal data outputs. To assess the internal reliability, Cronbach's α[47], McDonald's omega estimate[48], Guttman's Lambda 6 (G6), and Explained Common Variance (ECV) were calculated. Then, a test of dimensionality was conducted where the fit of a uni-dimensional Lavaan model with one latent variable was used to confirm whether the four ordinal questionnaire items point to a single variable – in this case, the amount of discomfort due to glare. A robust Weighted Least Square Mean and Variance adjusted (WLSMV) estimator for ordinal non-normally distributed variables was used for the Lavaan model.

Another set of statistical tests designed for dichotomous data was used to determine whether the two binary questionnaire items, "Binary-YesNo" and "Glare-indication-diagram" produced similar results in terms of association and reliability. First, McNemar's chi-squared test is performed to determine whether there were any significant differences in frequency between their outputs. To assess internal reliability, the Kuder-Richardson Formula 20 (KR20), which is similar to Cronbach's α but for dichotomous data, was calculated. To assess the correlation between the two outputs, the Phi coefficient is calculated instead of Spearman's rank correlation. There were no dimensionality tests performed between the two binary questionnaire items, but a Point biserial correlational test with each of the ordinal questionnaire output were then run to check if the binary questionnaires point to the same latent variable as the ordinal output. The "psych" package (version 1.9.12.31) in R (version

3.6.3) was used to perform reliability, dimensionality, and validity tests after normalizing responses (between 0 and 1) from the six questionnaire items.

The descriptive analyses in the preceding sections show that the responses to the four ordinal questionnaire items seem to agree with each other. To ascertain this, statistical tests on association and internal reliability are presented in this section, with separate sections on ordinal questionnaire items and binary questionnaire items.

i. Ordinal questionnaire items

First, a Pearson chi-squared test was performed across paired questionnaire items. The null hypothesis is that the questionnaire responses were independent and that no relationship exists between the categorical variables. The results rejected the null hypothesis with sufficient evidence, with all p-values being < 2.2e-16, at a significance value of 0.05 (p-values shown in the supplementary material). As a result, there is reason to believe that there is a significant relationship between ordinal questionnaire items.

In Table 3, pair-wise Spearman rank correlations ρ between questionnaire responses are shown. The output of ordinal questionnaire items generally shows strong intercorrelations, as the ρ are greater than 0.6. The strongest correlations are found between Interval-0-10 and Likert-4point, with a ρ of 0.85, and the second highest correlation is found between Likert-4point and OsterhausBailey-4point. All pairwise p-values show statistical significance of the Spearman rank correlation ρ values, rejecting the null hypothesis which is that there is zero correlation, as represented by "***" in the table.

Table 3 Spearman rank correlation rhos between Likert-4point, OsterhausBailey-4point, Interval-0-10, and Comfort-agreement questionnaire responses with ordinal data. ρ values show the strength of correlations, such as weak ($\rho < 0.4$), moderate ($0.4 \leq \rho < 0.6$), and strong correlations ($\rho > 0.6$) [49]. "***" indicates p-value < Bonferroni-corrected significance level of 0.0083 ($\alpha = 0.05/6$) for six comparisons.

	OsterhausBailey-4point	**Interval-0-10**	**Comfort-agreement**
Likert-4point	0.80***	0.85***	0.71***
OsterhausBailey-4point	-	0.79***	0.68***
Interval-0-10	-	-	0.76***

Following the analysis of pair-wise correlations, psychometric statistics testing for the internal reliability of the ordinal questionnaire items was conducted and the results are shown in Table 4. The Cronbach's α, Guttman's Lambda 6 (G6), Omega total, and Explained Common Variance (ECV) are all greater than 0.9, indicating a high level of internal consistency among the four questionnaire items[50]. A Cronbach's α above 0.7 shows acceptable internal reliability but one must keep in mind that α increases with the number of items tested and average item intercorrelation[51]. To this end, we found that the internal reliability does not increase more than 0.93 when any of the questionnaire items are removed from the group as shown in Table 5. This demonstrates that none of the questionnaire items reduces the internal consistency of the four items and that they have overall high consistency with each other.

Table 4 Psychometric statistics for internal reliability for Likert-4point, OsterhausBailey-4point, Interval-0-10, and Comfort-agreement questionnaire responses.

Psychometric Statistics	
Cronbach's α	0.93
Guttman's Lambda 6 (G6)	0.92
Omega Total	0.94
Explained Common Variance (ECV)	0.95

Table 5 Results of Cronbach's α, if each questionnaire item is removed.

Item dropped	Cronbach's α
Likert-4point	0.90
OsterhausBailey-4point	0.91
Interval-0-10	0.89
Comfort-agreement	0.93

A test for dimensionality was performed for the ordinal questionnaire items to see if the outputs point to a single variable. From the Lavaan model fit with 1 latent variable, the Comparative Fit Index (CFI) and Tucker-Lewis Index (TLI) are both greater than 0.95 (Table 6), indicating that responses from the four ordinal questionnaire items point to a singular variable[52]. The root mean square error of approximation (RMSEA) is 0.094, greater than 0.08, which has been proposed as a marginally acceptable minimum threshold for other Lavaan model estimators[53] although a specific RMSEA threshold for the Lavaan model specifically with the WLSMV estimator is not established yet[54]. Hence, the confirmation of the Lavaan model fit with 1 latent variable indicates that the four ordinal questionnaire items, OsterhausBailey-4point, Likert-4point, Interval-0-10, and Comfort-agreement, all describe one variable.

Table 6 Lavaan unidimensional model results fit indexes, using the robust weighted least square mean and variance adjusted (WLSMV) estimator.

Lavaan model fit with 1 latent variable (w/ estimator: WLSMV	
Comparative Fit Index (CFI)	0.989
Tucker-Lewis Index (TLI)	0.967
Root Mean Square Error of Approximation (RMSEA)	0.094

ii. Binary questionnaire items

McNemar's chi-squared test for paired dichotomous data was used to test the association between binary questionnaire items, where the null hypothesis is that the two outcomes are the same. In this case, we refer to the response outputs of Binary-YesNo and Glare-indication-diagram. Using a significance level of 0.05, there is sufficient evidence to reject the null hypothesis, with a chi-squared value of 79.1 and p-value of < 2.2e-16. As a result, the alternative hypothesis (that there is a significant difference between these two outputs) is accepted. This demonstrates that the response distributions from the two binary questionnaire items differ significantly.

Then, instead of Spearman rank correlation, the Phi coefficient is used to determine the strength of association between dichotomous data from the binary questions. According to the Phi test coefficient of 0.65, the correlation between the outcomes of the two ordinal questionnaire items is considered strong according to the same criteria[49] used for Spearman rank correlation ρ. However, the correlation is not as strong as that between OsterhausBailey-4point and Likert-4point, which both have the same number of response items and have a paired Spearman rank rho of 0.80, as shown previously in Table 3.

The internal reliability between the two binary outputs was tested. The KR20 value is found to be 0.79 which is lower than the Cronbach α of the ordinal questionnaire items. In contrast to Cronbach's α found between the ordinal questionnaire items (which was 0.93), the outputs between binary questionnaire items point to different thresholds of glare. Nevertheless, the outputs from the binary questionnaire items still significantly correlated with that of the ordinal questionnaire items, as shown from Point biserial correlational test results shown in Table 7. This indicates that their output still corresponds well to that of the ordinal questionnaire items.

Table 7 Point biserial correlation ρ between the output of binary questionnaires to that of ordinal questionnaire items. ρ values show the strength of correlations, such as weak ($\rho < 0.4$), moderate ($0.4 \leq \rho < 0.6$), and strong correlations ($\rho > 0.6$)[49]. "***" indicates p-value < Bonferroni-corrected significance level of 0.000625 ($\alpha = 0.05/8$) for eight comparisons.

	Likert-4point	**OsterhausBailey-4point**	**Interval-0-10**	**Comfort-agreement**
Binary-YesNo	0.69***	0.64***	0.70***	0.62***
Glare-indication-diagram	0.66***	0.63***	0.63***	0.53***

iii. Construct validity check with an open-ended question

To confirm the construct which the six questionnaire items solicit is indeed about discomfort glare, their outputs were tested for correlation against the results of the open-ended question, Binary-Open. The distribution of categorized responses from Binary-Open is shown in Figure 4. As shown by the Phi coefficient and Point biserial correlation results between Binary-Open and the respective questionnaire item outputs in Table 8, significant correlations with moderate strength were found except for the Glare-indication-diagram. This proves that the latent construct that was solicited in the survey questionnaire items was indeed regarding discomfort glare. The results from Binary-Open also show that participants reported glare or uncomfortable lighting in the open-ended question even before being asked specifically about glare in the questionnaire.

Table 8 Phi coefficient and Point biserial correlation ρ between the output of the open-ended question (Binary-Open) to that binary and ordinal questionnaire items, respectively. ρ values show the strength of correlations, such as weak ($\rho < 0.4$), moderate ($0.4 \leq \rho < 0.6$), and strong correlations ($\rho > 0.6$)[49]. "***" indicates p-value < Bonferroni-corrected significance level of 0.0083 ($\alpha = 0.05/8$) for eight comparisons.

	Phi coefficient		**Point biserial correlation ρ**			
	Binary-YesNo	Glare-indication-diagram	Likert-4point	OsterhausBailey-4point	Interval-0-10	Comfort-agreement
Binary-Open (n = 137)	0.53***	0.36***	0.52***	0.42***	0.60***	0.50***

5 Discussion

From the conducted comparability study, it appears that the outputs of the four ordinal questionnaire items with multiple-point response scales, namely OsterhausBailey-4point, Likert-4point, Interval-0-10, and Comfort-agreement, are inter-dependent, correlate with each other, have high internal reliability, and describe the same latent variable. This means that the distributions of their results are comparable and assess the same construct but still differ in terms of the level of resolution and semantic interpretations of their response items. Meanwhile, it also revealed that the outputs of two binary questionnaire items, such as Binary-YesNo and Glare-indication-diagram, also point to the same latent variable but seem to be solicit different thresholds of glare.

a. Interpretations of response items in questionnaires

Despite the high correlation between the outputs of ordinal questionnaire items, there still exist slight nuances and differences between them. Although the OsterhausBailey-4point and Likert-4point both have 4-point response scales that produce similar results, the semantics used in the response items in OsterhausBailey-4point may point to the noticeability instead of the intensity of discomfort glare despite being somewhat in increasing intensity order. For example, some participants may select "Noticeable" glare on the OsterhausBailey-4point indicating that they visually noticed a bright glare source, but that glare source may not generate discomfort for them as they simultaneously also select "Not at all" on the Likert-4point (Figure 8).

The findings of this study also begin to demonstrate the corresponding relationships between the response outputs of these six questionnaire items and the flow of responses between them. For example, while a “6” and above on the Interval-0-10 scale may not have had a clear meaning tied to it so far, this study shows that it may correspond to “moderate” glare and above on the Likert-4point, as seen in Figure 4. As the binary questionnaire items show results in a lower resolution because there are only two response items to choose from, we may compare their output to corresponding response items on ordinal scales as well. For example, from the Binary-YesNo question, the distribution of "Yes" responses corresponds to the distribution of half of the "Noticeable" responses plus the "Disturbing" and "Intolerable" responses from the OsterhausBailey-4point question.

In addition, the Glare-indication-diagram seems to ask for a qualitative concept of where the glare source is located rather than the reporting of discomfort due to glare. Although it is asked as a single question, it still has a conditional structure in which it asks if the participants feel discomfort from a glare source and if so, to color the location on the diagram. Hence, this questionnaire item is useful for qualitatively identifying the sources of glare from the user’s perspective, as well as to identify whether participants were attentive and understood the survey if the locations of the indications are not random. Interestingly, for specific conditions, some participants indicated the darker areas of their field of view as sources of glare, implying that they associated this with the effect of contrast instead. Such responses may thus provide interesting spatial feedback on whether the source of discomfort is due to excessive brightness (saturation effect) or contrast. Furthermore, given the threshold for an indication on the Glare-indication-diagram for the OsterhausBailey-4point is approximately "Noticeable". This means a marking on the diagram represents a glare source noticed by the participant, even if it is just slightly bothersome. On the other hand, a positive response to Binary-YesNo corresponded to a higher degree of glare on the OsterhausBailey-4point response scale. However, this could also be due to a different understanding of a slightly nuanced wording in these two binary questionnaires: the Binary-YesNo question asks if *discomfort* due to glare is experienced while the Glare-indication-diagram instead asks if *uncomfortable* glare is experienced.

b. Impact of the skip sequencing method

The usage of a two-step skip sequencing method has been suggested in recent publications on evaluating discomfort glare[11,38]. The method involved asking a binary question if the participant is experiencing discomfort glare first, then if the answer is “No”, no subsequent question is asked. If the answer is “Yes”, the participant is asked to evaluate the amount of discomfort from glare on a 6-point numerical response scale from 1 to 6, with 1 labelled “Very small amount” and 6 labelled “Very large amount”. As shown in the results of this study, we found that participants who answer “No” to the Binary-YesNo question do not directly correspond to “0” on the Interval-0-10 response scale, nor to the null response item “Not at all” in the Likert-4point. They also answer “Slightly” or “Noticeable” to other questionnaire items like Likert-4point and OsterhausBailey-4point, as shown in Figure 6. This might be because the participants have more options in the ordinal response scales and can choose a better fitting response for the degree of discomfort glare they experience, than in the binary response scale.

Using skip sequencing may include 'non-response' and 'response' errors in the second question due to item response errors in the initial question[55]. Hence, while the Binary-YesNo question may reduce the duration of the experiment by not asking more than 1 question when not necessary, it can cause non-response errors in the subsequent question. 'Non-response' errors occur when participants answer "No" to the first question and hence do not get to respond to the second question. As a result, this may change the distribution of the responses to the second question. For example, in this case, around a quarter of the participants answered "No" to Binary-YesNo but answered "Noticeable" to OsterhausBailey-4point.

To check for the significance of the difference in the responses may be in the second question because of such non-response errors, we simulated the skip-sequencing method by comparing two groups – one with data points where participants answered “No” to Binary-YesNo are forcefully mapped to the null option of the response scale (e.g., “Imperceptible” in the OsterhausBailey-4point), and the second group has all data points kept regardless of the Binary-YesNo output. Hence, to see if the distribution of results in the two groups is significantly affected by skip sequencing, a Wilcoxon signed rank test was used, where the null hypothesis is that there is no significant difference between two groups of ordinal data, as shown in **Error! Reference source not found.**. Since the p-values are less than the Bonferroni-corrected significance level of 0.0125 (α = 0.05/4) for four comparisons, we can reject the null hypothesis for all four tests. This shows that there can be a significant impact of skip-sequencing on the distribution of responses in an ordinal response scale in the second question due to potential non-response errors, as illustrated in Figure 9. However, we observed that the percentage of “disturbing and above” responses on OsterhausBailey-4point question, which is typically used in glare studies, remains similar in both cases, with or without skip-sequencing. This is similar for Likert-4point (“Moderately and above”), Comfort-agreement (“Disagree and above”) and Interval-0-10 (6 and above). Nevertheless, skip-sequencing significantly changes percentages for lower response items and should not be applied if one is interested in lower glare evaluation ranges.

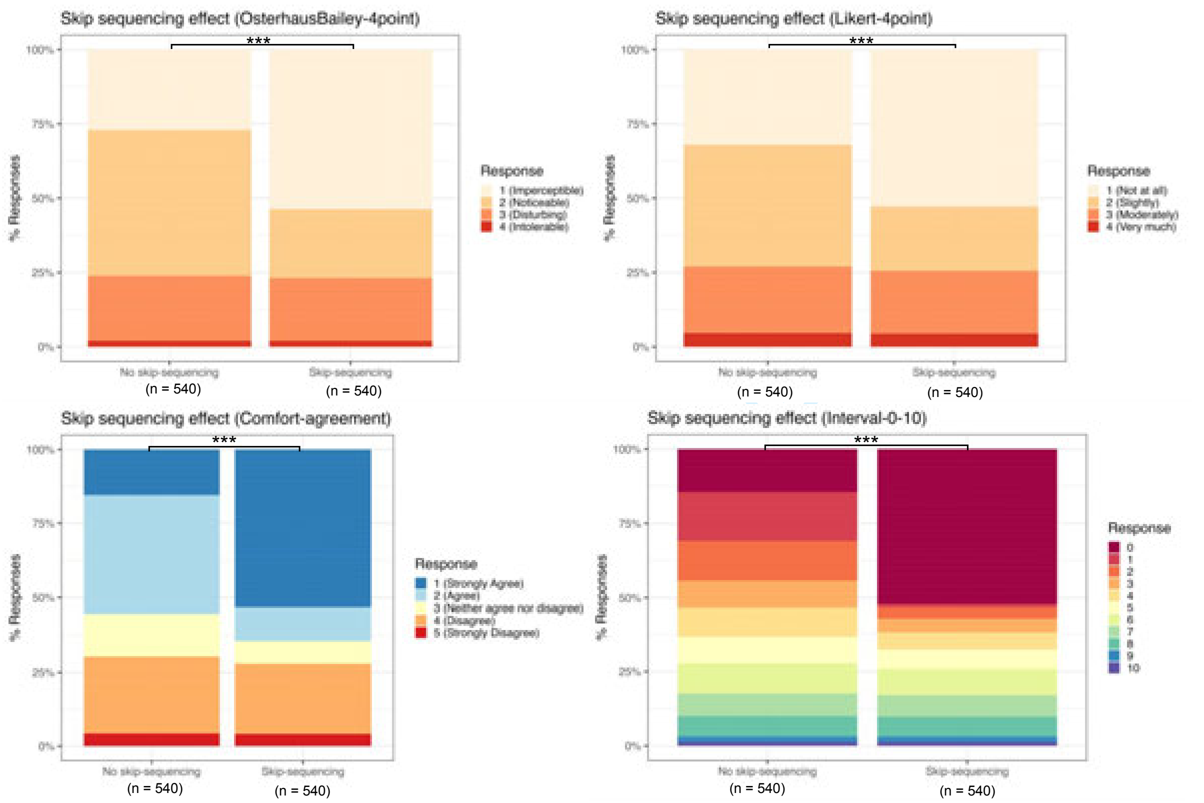


Figure 9 Stacked bar plots showing the effects of a simulated skip-sequencing method on the distributions of participants’ responses in the four ordinal questionnaire items (without the null response item) and without a skip-sequencing method. Significant effects are labelled “***” based on a Wilcoxon signed rank test.

Table 9 p-values of the Wilcoxon signed rank tests run between data with simulated skip-sequencing method and without. "***" indicates p-value < Bonferroni-corrected significance level of 0.0125 (α = 0.05/4) for four comparisons.

	Likert-4point	OsterhausBailey-4point	Interval-0-10	Comfort-agreement
Effect of skip sequencing method	0.00013***	3.14e-07***	5.98e-06***	< 2.2e-16***

One could argue, that subjects who answered "No" on the Binary-YesNo question, but went on to answer a non-null response on other questions can be considered as unreliable subjects. In general, unreliable subjects would add noise to the data and therefore result in a lower internal reliability between the questionnaire items. Therefore, to check if the inclusion of the responses of such subjects lowers the reliability, we conducted following test: We applied the skip-sequencing on the data and then removed the null-responses (i.e., participants answering "No" on the Binary-YesNo question). We call this *dataset1*. To create *dataset2,* we did not apply skip-sequencing but only removed the null responses from the ordinal questionnaires. The null answers from both datasets had to be removed for two reasons: 1) the skip-sequenced data would contain a large amount of identical data (100% of the null responses would be then per definition exactly the same for all scales) which would bias the result and 2) only a potential difference in the non-null distribution matters for this analysis. For both datasets, we applied then the internal reliability tests and found that they have similar internal reliability as shown in Table 10. Hence, these results indicate that these subjects are not unreliable because the internal reliability between ordinal questionnaire items did not increase when skip-sequencing was applied. This suggests that the skip-sequenced data is as equally consistent as non-skip-sequenced data, while producing a different overall distribution as previously shown in Figure 9 and Table 9.

Table 10 Psychometric statistics for non-null responses from Likert-4point, OsterhausBailey-4point, Interval-0-10, and Comfort-agreement with and without skip-sequencing.

Psychometric Statistics	***dataset1*** (Non-null responses and skip-sequencing applied, n = 240)	***dataset2*** (Non-null responses, n = 330)
Cronbach's α	0.88	0.89
Guttman's Lambda 6 (G6)	0.85	0.87
Omega Total	0.91	0.92
Explained Common Variance (ECV)	0.85	0.95

c. Limitations

Some limitations of this study include, first, that the questionnaires were only tested in English and no other translations were tested, which means that the results of this study are limited to questionnaires administered in English. Future research may want to discuss how to effectively translate across several languages and to test if the relationships between the original English questionnaire items and translated ones stay true.

Although there are some devices used in clinical determinations of individuals' discomfort glare through electromyograms[56], or to measure an individual's sensitivity to discomfort glare[57], these objective methods are usually considered invasive with the attachments of electrodes around the eye in the former or cover the entire field of view in the latter. Physiological and ocular data such as pupil diameter, pupil unrest index, and eye fixation rate were also found to correlate with glare stimuli[38] but no thresholds to describe glare degree were derived. Artificial intelligence has also been trained to predict if the occupant experiences discomfort glare[58]. However, in most of these studies, the "ground truth" of the degree of discomfort glare perceived is still solicited from subjective evaluations through the choice of a single questionnaire item. Even though objective measures exist, as previously stated, there is still a strong reliance on questionnaires, as they are used to derive semantic meaning for the degree of glare even for objective measurements. Hence, the construct validity of questionnaire items may be proven through the associative relationship with physiological and ocular markers that correlate with glare stimuli, but these objective measures may not convey semantic meanings of the degree of glare perceived (criterion-related validity).

As the three user studies cover different ranges of glare, one may question if there is a range effect, where the within-study analysis would output different results from that of the consolidated dataset. We checked that the conclusions made in the overall study do correspond to that of the individual dataset, indicating no effects of range bias (See detailed results in supplementary material). In addition, to check for stimulus range bias such as those found in adjustment-type studies[59], we re-ran the analysis for only the first scene evaluated by each participant, such that there is no range of stimuli to bias the results of the evaluations. Similarly, the conclusions did not deviate from that of the full dataset, suggesting that there was no significant stimuli range bias in the glare evaluations of the underlying experiments.

The small selection of questionnaire items or more specifically the number of tested items is a limitation since this research is not a representative testing of all so far used glare scales. Considering experimental constraints regarding increased duration of experimental phases when adding more questionnaire items and avoiding annoyance of the subjects when asking too many questions in the same direction, we had to limit the number of questions to a reasonable number, which is six.

Although the response items in the selected questionnaire items do have different semantics, the study of semantics is currently outside the scope of this investigation. In future discussions on glare questionnaire design or standardization, as well as when determining which questionnaire item to apply, it may be worth noting the necessary range, meaning, and informativeness of semantical categorizations that are required for visual comfort criteria in spaces. The semantics of the response items should ultimately depend on which questionnaire item may provide sufficient differentiated “levels” of discomfort from glare that will be useful for its purpose. For example, considerations of semantics are needed when researching temporal aspects of annual glare requirements - current recommendations of EN17037 recommend that DGP does not exceed 5% of occupied time annually with “disturbing” or “intolerable” glare based on the OsterhausBailey-4point scale. In addition, the semantic biases that may occur with translation processes between languages may lose original meanings or may not exist in different languages altogether[8].

6 Conclusion

To evaluate if the type of questionnaire item captures corresponding or contradictory distributions of glare responses, we selected and compared six questionnaire items for evaluating discomfort glare in rating-type experiments. They were subsequently administered to each participant in a randomized order when implemented in three user studies and resulted in a diverse dataset of lighting conditions with 540 user assessment data points from 149 individuals, where the outputs of six questionnaire items were examined pairwise descriptively and then tested for association, reliability, and dimensionality.

The first finding of the study is that the outputs of ordinal questionnaire items tested were found to have strong correlations with each other, have excellent internal reliability, and point to the same latent variable. We make the reasonable assumption that this variable refers to the degree of discomfort caused by glare, backed up by the construct validity check compared to the open-ended question. This finding signifies that the four tested ordinal questionnaire items are interchangeable to some extent. This means that their results distributions are comparable and assess the same construct, but they differ in terms of informativeness (the level of resolution and semantic interpretations of their response items). We also confirmed the validity of the latent construct using responses from Binary-Open only for the first evaluation per participant, an open-ended question asked before the six questionnaire items were administered.

The response outputs of the Binary-YesNo and Glare-indication-diagram questionnaires correlate well with those of ordinal ones, as well as responses from the open-ended question, Binary-Open. This means they solicit about the same latent construct, which is the degree of glare experienced. Results also show that the two tested binary questionnaires point to different thresholds of glare.

Overall, this study provides a scientific basis for future psychometric research and discussions about the usability and applicability of questionnaire items for collecting user evaluations of discomfort from glare in rating-type studies in daylight. All six tested questionnaire items point to the same latent variable and therefore can be used in daylight glare studies that use similar rating-type procedures. They mainly differ in the granularity and the levels and thresholds of glare they solicit and therefore researchers should select them depending on their research question. Nonetheless, we recommend researchers to use at least two types of questionnaire items to ensure that participants understand the questions, especially if items are translated or if people with diverse backgrounds participate in the studies. Our findings hope to support future discussions on glare questionnaire standardizations and as such, this study does not intend to specifically recommend any of the tested glare questionnaire items. We believe that more psychometric research is also needed to ascertain these findings for adjustment-type studies commonly conducted for evaluating glare from electric light sources.

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Education

Feb 2019- May 2023	**Ph.D. Civil and Environmental Engineering** École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland Supervisors: Prof. Marilyne Andersen and Dr. Jan Wienold. Dissertation: Influence of macular pigment and color of (day)light on discomfort glare.
Sep 2016- Dec 2018	**M.S. Information Technology in Building Science (GPA: 9.6/10)** International Institute of Information Technology (IIIT), Hyderabad, India Supervisor: Dr. Vishal Garg. Dissertation: Daylighting estimation for window shade control using high dynamic range imaging
Aug 2010- Jan 2015	**B.Arch. Architecture (GPA: 8.5/10)** Maulana Azad National Institute of Technology (MANIT), Bhopal, India

Research & Industry Experience

Feb 2019- ongoing	**Doctoral Assistant** EPFL, Lausanne, Switzerland Work: Doctoral thesis, teaching assistantship and student supervision
Feb - Aug 2018	**Research Fellow** Building Technology and Urban Systems, Lawrence Berkeley National Laboratory (LBNL), California, United States Supervisors: Dr. Luis Fernandes and Christian Kohler Work: Implementation of HDR images to measure daylight glare, illuminance and CCT. Evaluation of battery-backed LEDs under demand response and real pricing scenarios.
Sep 2016- Jan 2019	**Graduate Research Assistant** IIIT Hyderabad, India Work: Master thesis, teaching assistantship and student supervision
Oct 2015- Aug 2016	**Virtual Construction and Design engineer** Vconstruct Pvt. Ltd., Pune, India Work: Project lead for facility management, BIM co-ordination, Quality assurance, 4D-simulations, 3D scanning and virtual mock-ups for various construction projects. Major projects: Facebook data center, LinkedIn campus, Tehama residential towers.

Fellowships & Awards

Recipient of BHAVAN Fellowship (Building Energy Efficiency Higher and Advanced Network) from the Department of Science & Technology (DST), India for a six-month research internship at LBNL, California, USA.

Best paper award at ASIM 2018 conference in Hong Kong for the paper "Circadian lighting in a space daylit by a tubular daylight device".

Publications

Peer-reviewed Journals

S Jain, C Karmann, J Wienold, Behind electrochromic glazing: Assessing user's perception of glare from the sun in a controlled environment, Energy and Buildings, Feb 2022.

S Jain, and V Garg. A review of open-loop control strategies for shades blinds and integrated lighting by use of real-time daylight prediction methods. Building and Environment, May 2018.

S Jain, J Wienold, M Lagier, A Schuler, M Andersen, Perceived glare from the sun behind tinted glazing: Comparing blue vs. color-neutral tints. Building and Environment, 2023.

Under review/ preparation

G Quek, **S Jain**, C Karmann, C Pierson, J Wienold, M Andersen, A critical analysis of questionnaire items for discomfort glare studies in daylit spaces, Lighting Research & Technology 2022 (Under Review)

S Jain, J Wienold, A Kawasaki, C Eandi, S Gisselbaek, M Andersen, Influence of macular pigment on the sensitivity to discomfort glare from daylight in workplace scenario, Scientific Reports by Nature (Submitted).

S Jain, J Wienold, M Andersen, Influence of color of glazing on human perception of discomfort glare from daylight, Color Research & Applications (Submitted).

Peer-reviewed Conferences

S Jain, J Wienold, M Andersen, Comparison between CIE 2° and 10° field photopic luminosity functions V(λ) for calculating daylight discomfort glare metrics, Lux Europa 2022, Prague, Czech Republic.

S Jain, J Wienold, M Andersen, Effect of window glazing color and transmittance on human visual comfort, PLEA 2022, Santiago, Chile.

J Wienold, **S Jain,** M Andersen, Transmittance thresholds of electrochromic glazing to achieve annual low-glare work environments, Nordic IBPSA 2022, Copenhagen, Denmark.

S Jain, J Wienold, M Andersen, On Sensitivity to Glare and Its Relationship with Macular Pigment, PROCEEDINGS of the Conference CIE 2021, Malaysia.

S Jain, C Karmann, J Wienold, Subjective assessment of visual comfort in a daylit workplace with an electrochromic glazed façade, Journal of Physics: Conference Series, 2021.

S Jain, J Wienold, M Andersen, Glare assessment in a daylit workplace from a physiological perspective, ANFA 2021 Symposium–Quantified Buildings, Quantified Self, California.

S Jain, L Fernandes, C Regnier, V Garg. Circadian lighting in a space daylit by a tubular daylight device. Asia Conference of International Building Performance Simulation Association ASim 2018, Hong Kong.

Presentations

- **S Jain,** What factors influence human visual comfort perception? Evaluating the effect of color of (day)light and eye physiology on discomfort glare in workplace scenarios. The axis Integrated Design, Architecture and Sustainability (IDEAS), Oct 25, 2022, EPFL, Switzerland. (Presentation)
- **S Jain**, Influence of Daylight Spectrum filtered by colored glazing on discomfort glare perception, Daylight Academy Annual Conference & General Assembly, Oct 2022, Zürich, Switzerland (Poster presentation)
- **S Jain**, Spectral discomfort glare sensitivity in daylit Environment, EDCE Research Day, Sep 2022, Switzerland. (Poster presentation)
- **S Jain**, Does glazing color influence our perception of discomfort glare from daylight? Build for Life, VELUX Daylight Symposium 2021, Copenhagen, Denmark. (Invited talk)
- **S Jain**, J Wienold, Glare behind blue (electrochromic) glazing, 19th Annual International Radiance Workshop, Bilbao, Spain, 2021 (Workshop Presentation)

Teaching Experience

Summer 2022 **Co-Instructor**
Center of Environment Planning and Technology (CEPT), Ahmedabad, India
Summer school on "Daylight beyond codes: Decoding daylight in Indoor spaces"
Level: Undergraduate and graduate students (≈20)

Fall 2019-2021 **Teaching Assistant**
EPFL, Switzerland
Course: "Comfort and Architecture: Sustainable Strategies"
Level: Graduate students (≈40)

Summer 2018 **Co-Instructor**
Workshop on "Building Simulation for Energy Conservation Building Codes 2017", Hyderabad, India

Fall 2017 **Teaching Assistant**
IIIT Hyderabad, India
Course: "C Programming for Engineers"
Level: Graduate students (≈30)

Student supervision

Fall 2022 **Master Thesis Supervision**
Oscar Fischer, MSc Microtechnology, EPFL, Switzerland
Evaluation of gaze behavior and facial responses to discomfort glare under colored daylighting sources

Fall 2021 **Semester Project Supervision**
Kaan Okumus, Mihaela-Diana Zanoaga, Roxane Burri, MSc Computer Science, EPFL, Switzerland
Deep learning-based Discomfort Glare Detection using image-based neural network models

Spring 2021 **Master Thesis Supervision**
Macha Bhargav, MTech Building Energy Performance, Center of Environment Planning and Technology (CEPT), Ahmedabad, India
Exploring the capabilities of Raspberry Pi HQ camera for generating luminance maps in indoor daylit environments.

Summer 2017 **Summer Project Supervision**
Souvik Das, Sai Tanya, and Utkarsh Kumar, BTech Engineering and Architecture
Summer internship on “Smart daylight glare control system” funded by Sage glass.

Committees & services

Reviewer for Scientific Journals: Building and Environment and Journal of Building Engineering

International Scientific Committee Member CIE TC3-57 on “Eye-physiology based glare sensation model”. (2021-)

IEA (International Energy Agency) member on the task “Low Carbon, High Comfort Integrated Lighting”. (2022-)

ASHRAE Student member American Society of Heating, Refrigerating and Air-Conditioning Enginee
(2016- 2018)

Volunteer tutor at AshaKiran (‘ray of hope’), Hyderabad, India (2016-2018)

Volunteer tutor at NSS (National Service Scheme), Bhopal, India (2011-2013)