IS THERE AN EFFECT OF MACULAR PIGMENT DENSITY ON DISCOMFORT GLARE IN INDOOR DAYLIGHT CONDITIONS?

Sneha Jain[1], Caroline Karmann[1,2], Jan Wienold[1], Marilyne Andersen[1]
[1] Laboratory of Integrated Performance in Design (LIPID), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, SWITZERLAND,
[2]Laboratory of Architecture and Intelligent Living (AIL), Karlsruhe Institute of Technology (KIT), Karlsruhe, GERMANY
sneha.jain@epfl.ch

Abstract

Discomfort glare from daylight can lower productivity and hinder effective use of daylight in buildings. Existing glare prediction models have limitations in accounting for the large inter-individual differences, mainly due to unknown physiological factors underlying discomfort glare. Our study aims to determine whether macular pigment optical density (MPOD) in the human retina influences individual glare sensitivity in indoor daylit environments. We conducted user studies involving 149 participants in office-like settings, and evaluated their glare sensitivity to visible sun-disc behind either colour-neutral glazing or saturated blue-coloured glazing, both with very low visual transmittances. Findings revealed that in neutral daylit conditions, participants' measured MPOD did not have any significant influence on their glare sensitivity. However, in conditions where the sun was visible through blue-coloured glazing, participants with higher MPOD demonstrated lower sensitivity to glare. These findings elucidate the role of macular pigments on individual glare sensitivity and provide insights for future research.

Keywords: Daylight, Discomfort glare, Macular pigment, User assessment, Human eye

1 Introduction and background

Effective integration of daylight in buildings requires addressing and minimizing the problem of discomfort glare from daylight. Prolonged exposure to glare can lead to a degradation of visual performance, eye fatigue, and headaches (Hemphälä et al., 2021; Osterhaus, 2005). Discomfort glare is generally predicted by empirical glare models that quantify the characteristics of the luminous environment in one's field of view (FOV). While the empirical glare models allow a reasonable estimate of the average discomfort for a group of observers, they fail to account for the wide individual variability in glare perception observed in studies (Mainster & Turner, 2012).

The physiological rationale behind these variabilities remains largely unknown but previous literature has shown that certain anatomical features of the eye, more specifically, macular pigment density in the retina, can potentially cause variance in one's sensitivity to light and therefore influence glare perception (Whitehead et al., 2006). As light traverses through the eye, it passes through multiple layers, before reaching the photoreceptors and some of it is filtered by the yellowish macular pigments, composed of dietary carotenoids, present in the central region of the retina named macula. The macular pigments (MP), spread over ~3.0° along the vertical and ~6.7° along the horizontal axes in that region, are known to improve the visual function by attenuating the short-wavelength (bluish) light and reducing the scatter, thus also effecting the spectral sensitivity of the eye. There exists a wide variability in the density of macular pigment across the human population, therefore causing a large variation in the amount of short-wavelength light processed by the retina (Stringham et al., 2010).

Due to these specific properties, macular pigment density has been studied several times for its influence on discomfort glare, notably in the context of preventive care for eye pathologies in the ophthalmological field. Several past studies have for instance shown that people with higher macular pigment density can tolerate higher levels of discomfort glare in the central (foveal) visual field (Hammond et al., 2013; Stringham et al., 2004, 2010, 2011; Wenzel et al., 2006; Wilson et al., 2021). Stringham et al also indicated that higher MP levels in the participants significantly improved their photostress recovery and visual performance in glare conditions (Stringham et al., 2011). Another study from the same authors showed that the participants with the broader spatial distribution of macular pigments (i.e. covering a greater range beyond fovea) had higher glare thresholds which were further confirmed by Wenzel et. al (Stringham et al., 2004; Wenzel et al., 2006). Hammond et al. also showed a significant contribution of MP in protection against disability and discomfort glare (Hammond et al., 2013). Most of these studies followed a similar methodology to induce and assess glare by using a Maxwellian-view optical system with a xenon lamp that has a spectrum close to solar spectra with higher emission in the shortwave region. 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. However, these glare conditions experienced by the participants 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 FOV. It is therefore still unknown whether an influence can be expected under daily indoor environments where the glare source is typically off-fovea.

To this end, our study aims to determine the influence of macular pigment density on glare sensitivity under indoor daylight conditions in workplace environments where the sun is visible through the window acting as a main glare source. We present the findings from three independent user studies that compare the measured MPOD with the glare evaluations done by participants under daylit spaces.

2 Method

To determine the influence of MP on glare sensitivity, we followed a psychophysiological approach in which participants' glare sensitivity in daylit office settings was compared to the measured macular pigment density. Three independent user studies, involving a total of 149 participants, were brought together to investigate the effect of MP on glare sensitivity. These three studies were designed with their own independent goals but followed a similar protocol. In all three studies, participants were exposed to pre-defined experimental conditions with the direct sun as the glare source in their near-peripheral FOV. In Study I, participants were exposed to four color-neutral conditions with varying transmittances of the window from where the sun was visible ("Glare Window" in Figure 1) with a goal to compare participants glare perception with their MPOD measurements. In Study II, participants were exposed to four conditions that varied in terms of the color of the "Glare Window" (Figure 1) as red, green, blue and neutral colors. Study II was designed to determine the influence of color on the glare perception. We only evaluate the blue colored glazing condition from Study II since in the blue region MP have the highest attenuation effect. Study III was designed to determine the influence of view-out on glare where each participant was exposed to two conditions having either no view or clear view from the lower part of the glazing, whereas the glare levels changed between the participants. Details of the experiment setup and procedure are described in the following sections.

2.1 Experiment setup

All three studies were conducted on the EPFL campus in Lausanne, Switzerland (46°31'00.4" N, 6°33'47.1" E) with daylight as the only source of light. All the participants were healthy young adults aged between 18 to 35 without any ocular pathologies and with normal colour vision. The project protocol was approved by the cantonal ethics commission of Canton Vaud, Switzerland (ref. No. CER-VD 2020-00667). Participants gave written informed consent before the experiments and were compensated as per the local regulations. Table 1 lists the test rooms, characteristics of the participants, and duration of all the studies. Figure 1 shows the pictures taken during the experiments for each of the three studies. The window panels in figure 1 are labelled as i) 'Glare window', from where the sun is visible, ii) as 'View-out windows' that facilitate the view-out, and iii) as 'Daylight window' that was kept at higher transmittance aimed to maintain a minimum daylight level in the space.

Study I and Study II were conducted during winter time (between 09:00-14:30) in the same south-facing office-like test room one year apart from each other, whereas Study III was conducted during summer (between 15:30-19:30) in a west-facing office room. These specific periods were chosen to have the sun at low angles visible through the façade as a glare source. Each experiment session for one participant lasted around two hours. All three studies utilized a luminance camera *LMK 98-4 colour High-Resolution* with a *Dörr Digital Professional DHG* fish-eye lens (180° FOV, equidistant projection) and a neutral density filter (ND4 in Study I and Study III, a combination of two ND1.8 in Study II) to capture the scene at participant's eye level without any pixel overflow. The camera had a handheld illuminance sensor *LMT Pocket-Lux 2* mounted below the lens to measure and compare the vertical illuminance data to the illuminance values derived from the HDR images. Additionally, a horizontal illuminance sensor of the same type was used to measure the lighting levels on the desk.

Participants' macular pigment optical density (MPOD) was measured using a macular pigment screener device *QuantifEye MPS II* that estimated light absorption by macular pigments using the heterochromatic flicker photometry method. Measured MPOD values ranges from 0 to 1, where a lower value indicates lower density of MP and therefore, higher level of light hitting the macula.

Table 1– Key details of the three studies and the participants' demographics

Study	Test room	Testing period	Sample size	Age (in years)	Sex	Vision correction
I	South-facing office-like test room	Nov' 2020-Feb 2021 (09:00-14:30)	55	Min=18 Max=34 Mean=23	72% male 28% female	64% no correction 36% glasses/lenses
II		Nov' 2021-Feb 2022 (09:00-14:30)	55	Min=18 Max=30 Mean=22.6	71.5% male 28.5% female	54% no correction 46% glasses/lenses
III	West-facing actual office room	May-July 2021 (15:30-19:30)	39	Min=18 Max=35 Mean=21.2	57% male 43% female	64% no correction 36% glasses/lenses

Study I Study II Study III

Figure 1 – Images of the test room showing the tested façade and the participants performing the given tasks during the experiment in each of the three studies

2.2 Experiment Procedure and Questionnaires

All the experiments started with an introductory phase (~20-30 mins) under electric light that involved signing the consent form, explanation of the tests by a researcher, filling out the background survey, performing the MPOD eye test and baseline acuity and contrast sensitivity tests. This phase was followed by a small break (~5mins) where the participant was either asked to wear an eye mask and listen to music (study I and II) or to wait quietly in an artificially lit corridor (study III) while the researcher conducted the environmental measurements and prepared the test room for the next phase. Afterward, participants' glare perception was evaluated under daylight by exposing them to a number of pre-defined experimental conditions in counterbalanced order. Between each condition, participants took a small break to relax their eyes (again, either by wearing an eye mask (study I and II) or staying in the artificially lit corridor (study III). Each exposure involved a typing task (~5-10mins) to adapt to the lighting levels followed by survey questionnaires on an online platform, where participants rated their discomfort glare levels along with other IEQ parameters on different rating scales. A difference in Study III compared to the other two studies was that after this survey, participants continued to perform certain cognitive tasks under the same condition and reported their comfort levels again after 30 minutes of exposure before they went on with the next exposure. The data collected in these extra exposure tasks was not used in this study.

In this paper, we will evaluate participants' answers to selected questions asking about their discomfort glare perception. Two questions are evaluated, one on a binary scale and another on Likert four-point scale: 1. Do you experience discomfort from glare, at the moment? Yes/No. 2. How much discomfort due to glare are you experiencing, at the moment? Imperceptible/Noticeable/ Disturbing/Intolerable. Based on their answers to the binary glare question, participants who reported "Yes" were categorised as more sensitive to glare and participants who reported "No" were categorised as less sensitive to glare. We compared the MPOD measurements between the two groups to check for statistically significant differences.

2.3 Experimental conditions

In Study I and II, participants were exposed to four experimental conditions while in Study III, participants were exposed to two conditions. The analysis and description presented in this paper is restricted to glare evaluations based on the full set of Study I, only on the two blue glazing conditions from Study II, and only one evaluation per participant from Study III.

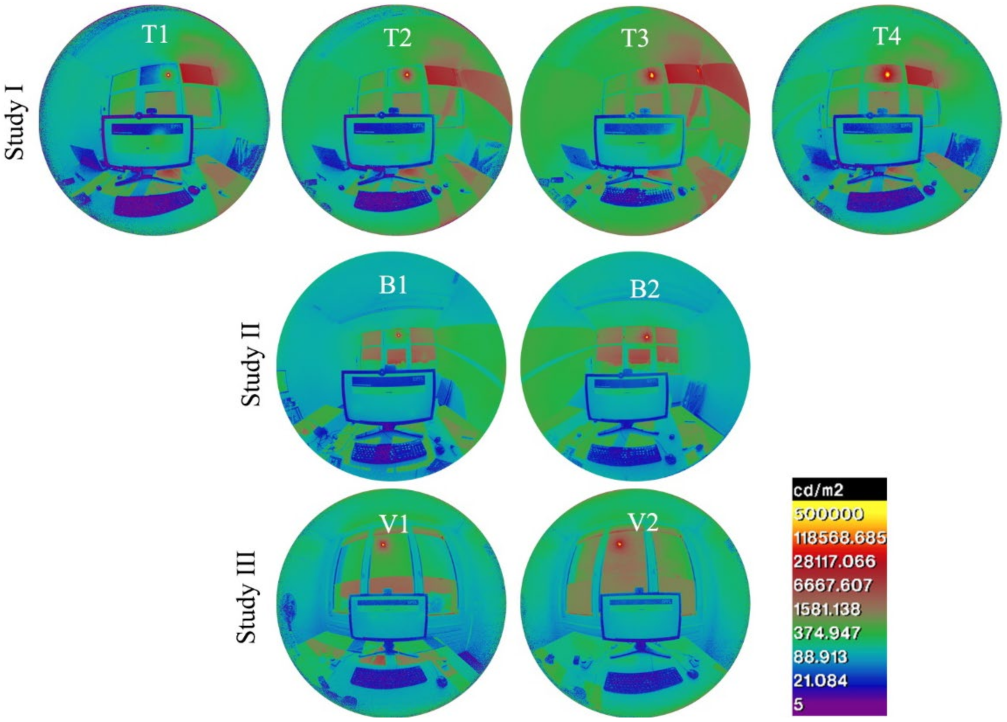

Figure 2 – Falsecolour luminance images of the evaluated experimental conditions in the three studies

In all three studies, participants were seated facing the window with the sun in their central visual field as shown in Figure 1. The experimental conditions were shown to the participants in randomized order and were created by changing the visible light transmittance of the window panes towards the sun (*Glare window* in Figure 1) by using removable filters on the fixed glazing. The filters were either colour-neutral (in Study I and Study III) or blue-coloured (in Study II) with specific transmittances* as listed in Table 3. Blue glazing was chosen since the light absorption by macular pigments is the highest in the short-wavelength region whereas colour-neutral glazing was chosen to represent regular office environments. Blue glazing had the peak transmission at 440 nm which is strongly absorbed by MP. The remaining windows (all colour-neutral), labelled as either *Daylight windows* or *View-out windows* in Figure 1 were kept at constant transmittances between the subjects for all the evaluated experimental conditions within each study. Figure 2 demonstrates the false-colour luminance images of the evaluated experimental conditions.

In Study I, participants were exposed to four experimental conditions, T1, T2, T3, and T4 that differed in *Glare window* transmittances as 0.36%, 1.25%, 3.4%, and 4.8% respectively (see Table 3). The *daylight window* was kept at maximum transmittance (79%) to maintain a minimum daylight level in the room (around 300 lux at the desk). Whereas *View-out windows* were kept at 4.8% to avoid glare yet maintain a clear view.

In Study II, each participant was exposed to four conditions differing in the colour of the *Glare window* (blue, green, red, and colour-neutral) of either low or extremely low transmittances. We only evaluated blue-coloured conditions, B1 and B2 varying between the participant in terms of *Glare window* transmittances as 0.39% and 2.25%. The remaining windows were kept at a constant transmittance of 8% to avoid glare and maintain a clear view.

In Study III, each participant was exposed to two conditions differing in terms of *View-out windows*, which were transparent (clear view) in one condition and translucent (no view) in another. The transmittance of the *Glare window* was changing between the participants from ~1.4% to ~3.5% to create two levels of glare V1 and V2, respectively. We only evaluated one condition per participant regardless of the access to the view out, since it did not have an influence on the glare ratings. Additionally, we did not evaluate the *No glare* conditions conducted on overcast days.

2.4 Data filtering

To ensure the homogeneity of the collected photometric data between the experiments, we applied specific data filtering criteria. Test cases where HDR images were found to be overexposed due to camera issues were removed. We discarded the test cases where the deviation in measured on-site global horizontal irradiance (GHI) was more than 25% ((GHImax - GHImin) / GHImean) to ensure stable daylight conditions during the entire exposure time and no intermittent clouds occluding the sun. In Study III, we exceptionally accepted a few data points where the GHI deviation was higher than 25% during the typing task period but not during the survey response period. Table 3 shows the final sample size in each experimental condition after filtering.

3 Results and Discussions

3.1 MPOD measurements of the participants

Table 2 provides a summary of descriptive statistics of measured MPOD values in three studies. Figure 3 shows the overlaid density plots of the measured MPOD in three studies. From Table 2 and Figure 3, we can infer that the MPOD distributions between studies I, II, and III are similar (Kolmogorov-Smirnov test: D=0.06, p=0.99), with a mean value of 0.49, 0.47, and 0.47, respectively. The MPOD ranges observed in our study are similar to previous studies with young and healthy adults (Loughman et al., 2010; Stringham & Snodderly, 2013; Wilson et al., 2021). The measured MPOD data is further compared with participants' glare sensitivity in section 3.3 with a hypothesis that participants with higher MPOD values are less sensitive to glare.

---

* Transmittance reported in study I and II were measured on a window test bed (refer (Jain et al., 2023)) while for study III, they were estimated based on manufacturer's data.

Table 2 – Descriptive statistics of participants measured MPOD values

Study	Mean	Median	Minimum	Maximum	Std. dev.
Study I	0.49	0.48	0.14	0.86	±0.17
Study II	0.47	0.45	0.19	0.82	±0.16
Study III	0.47	0.48	0.19	0.82	±0.14

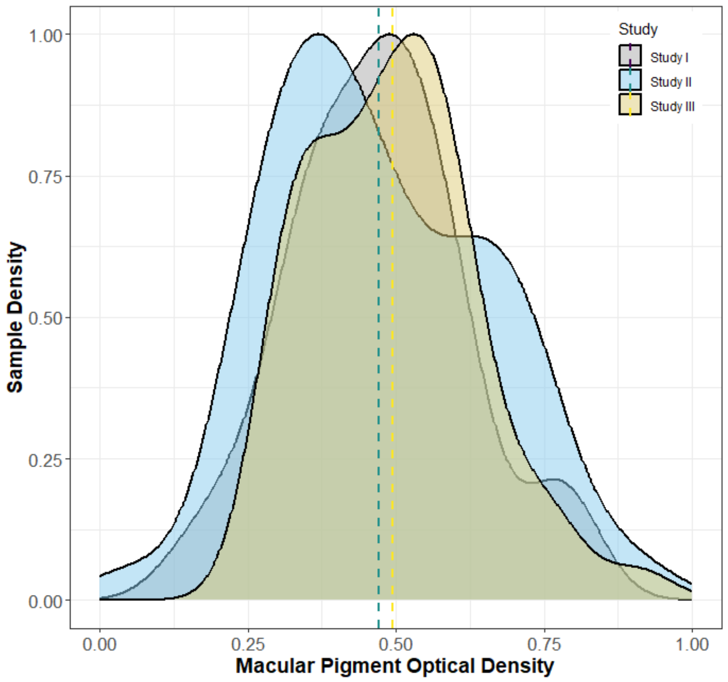

Figure 3–Density plots showing the distribution of measured MPOD (minimum value of right and left eye measurements) in three studies

3.2 Experimental conditions

To ensure participants were exposed to similar glare levels within each experimental condition in all the three studies, we analysed the distribution of photometric and geometric properties associated with the glare source. Table 3 shows a summary of the data collected from the measurements and HDR images that include the transmittance of the *Glare window*, mean vertical illuminance, mean sun luminance, mean Daylight Glare Probability (DGP), mean position index of the glare source, i.e., the sun, and mean viewing angle between the sun and the observer. As expected, the photometric quantities increase with the glazing transmittance, allowing more daylight in the space. Figure 4 shows the HDR image-derived DGP and sun luminance values during the exposure presented as boxplots with median values (the box plots in grey were not evaluated for the final analysis, see Section 3.3). It can be seen that the variance in sun luminance and DGP values within each condition is sufficiently low, indicating that participants were exposed to similar levels of glare within their respective experimental conditions. Therefore, we can evaluate the variability in participants' glare votes with similar glare conditions and relate it with their MPOD measurements.

Table 3 – Measured and HDR image-derived properties of experimental conditions

Study	Scene names	Sample size (after filtering)	Glare window τ_v (in %)	Mean E_v (lux)	Mean sun luminance (Millions cd/m^2)	Mean DGP	Mean position index	Mean viewing angle to the sun
Study I	T1	45	0.36%	1,770	2.6	0.35	3.3	32°
	T2	45	1.25%	2,200	9.8	0.44	3.3	32°
	T3	44	3.4%	3,300	28	0.54	3.3	32°
	T4	45	4.8%	4,800	46	0.62	3.3	32°
Study II	B1	25	0.39%	1,130	3.6	0.38	3.2	31°
	B2	25	2.25%	2,300	21.2	0.50	3.3	32°
Study III	V1	19	1.4%	1,973	15.5	0.40	7.2	45°
	V2	18	3.5%	3,680	42.2	0.54	5.5	40°

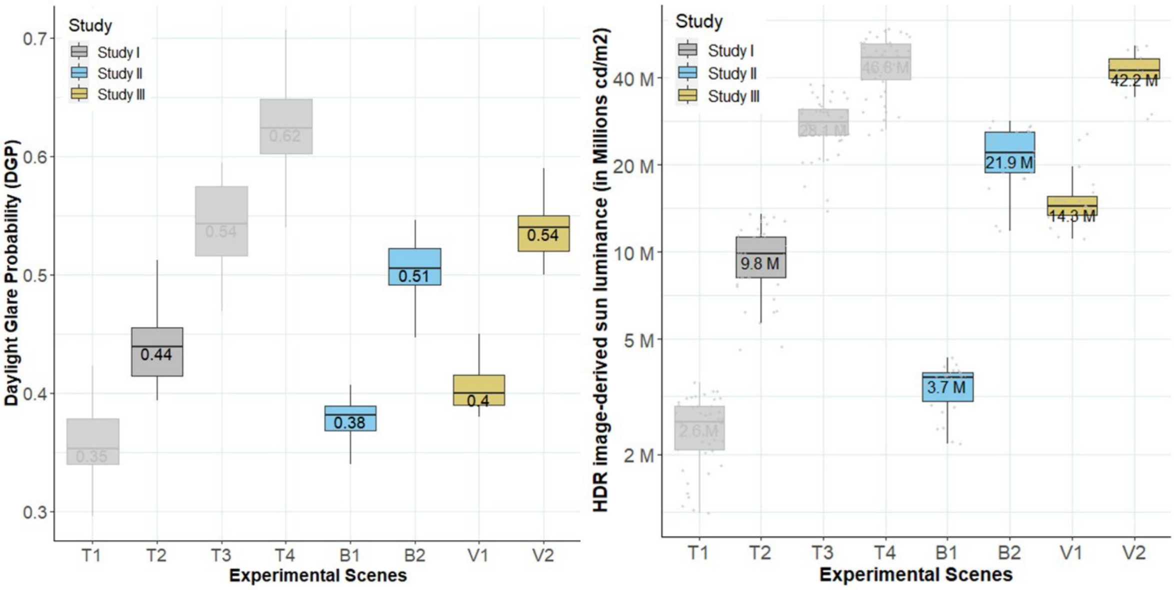

Figure 4 – Distribution of HDR image derives DGP (left) and sun luminance (right) values in all experimental conditions as boxplots with median values

3.3 Subjective discomfort glare responses

Figures 5 demonstrate the percentage distribution of discomfort glare responses from the participants in all the experimental conditions, rated on a binary *Yes/No* scale. As expected, a greater number of participants were experiencing discomfort from glare with an increase in the associated photometric values and the glazing transmittance (see Table 3). Additionally, 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. We also compared the binary glare question with the four-point glare question and found a similar trend of glare voting between the two questions, therefore, indicating an agreement. Most of the participants who answered *No* on the binary glare question tended to choose either the *Imperceptible* or *Noticeable* option on the four-point ordinal glare question.

From the available data, we decided to categorize participants who answered ‘Yes’ (Figure. 5) as the more sensitive to glare, while the remaining participants were categorizes as being less sensitive to glare. This grouping was primarily done to compare the measured MPOD values between these two groups and examine whether there were any differences in the MPOD levels. In order to conduct a between-subject comparison of participants’ MPOD levels and their glare sensitivity, we only considered unique participants and excluded repeated measures from each study. Therefore, in Study I out of the four conditions shown to the participants we selected condition T2 since it exhibited a more balanced distribution of participants in each category of less or more sensitive groups. As for Study II and Study III, all evaluations were already from the unique participants, therefore we utilized the complete dataset as shown in Figure 5. The analysis and outcomes are presented in the following section.

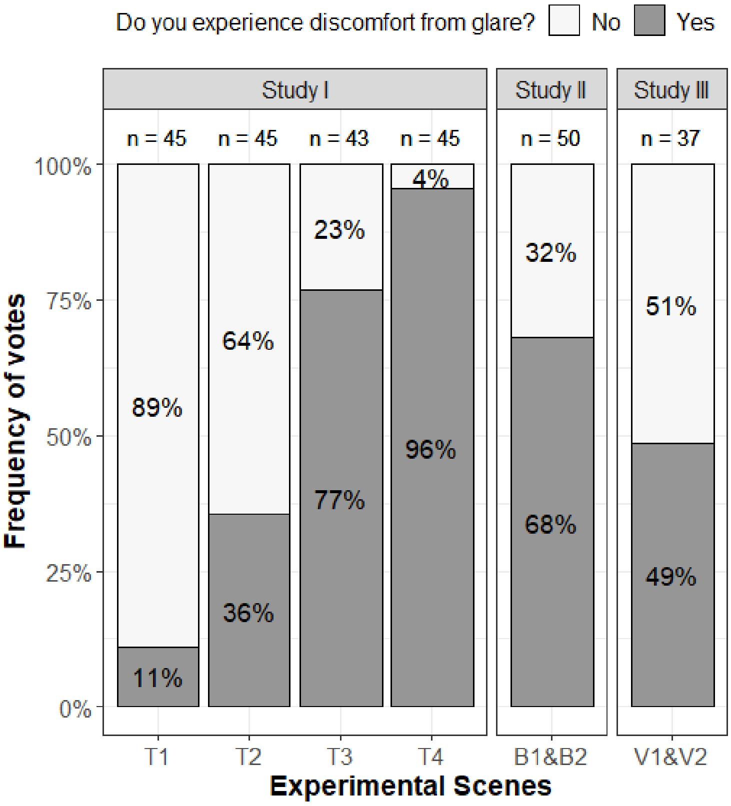

Figure 5–Stacked percentage bar chart showing the distribution of glare votes under all the experimental conditions on the binary glare responses

3.4 Influence of MPOD on discomfort glare

To compare the macular pigments measurements between two groups of participants, where one group is less sensitive to glare and the other group is more sensitive to glare, we used an unpaired two-sample Wilcoxon test (also known as Wilcoxon rank sum test or Mann-Whitney test). Since the two groups are independent (different participants) and the distribution of MPOD between the groups are not normally distributed (Shapiro-Wilk test, $p<0.05$), therefore, a non-parametric alternative to the t-test was used. The alternate hypothesis is that the less sensitive group has higher MPOD values compared to the more sensitive group. As shown in Figure 6, we were only able to prove this hypothesis in Study II with blue-coloured glazing (Wilcoxon, $p= 0.0049$) where the less sensitive group had a significantly higher median value of MPOD ~0.5 than the more sensitive group ~0.36. Whereas in Study I and Study II, both of which had colour-neutral glazing, we did not observe any significant differences in participants’ MPOD between the less and more sensitive groups.

Similarly, to assess the strength of the relationship between participants’ discomfort glare sensation and their MPOD measurements, we applied a point-biserial correlation, suitable for a binary outcome (yes/no glare question), and Spearman’s rank correlation, appropriate for an ordinal four-point outcome as shown in Table 4. Once again, we observed a statistically significant association between glare sensation and MPOD with a moderate effect size (rho=-0.40, p=0.005) based on Cohen's effect size threshold, but only in the case of Study II with blue-coloured glazing. Participants with denser macular pigments were better able to tolerate the glare from the sun filtered through the saturated blue glazing indicating that the spectral composition of the glare source plays a key role when it comes to the contribution of macular pigments in protection against discomfort glare.

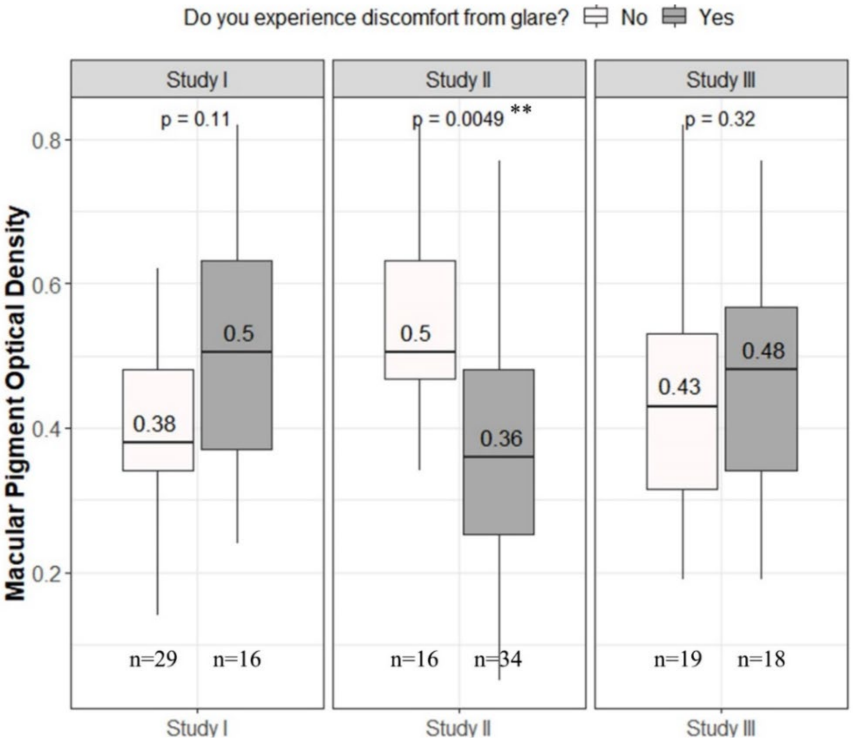

Figure 6 – Box plots comparing the differences in MPOD levels between the two groups of participants less sensitive and more sensitive to glare

Table 4 – Correlation coefficients between participants' subjective responses to glare and their measured MPOD values

Type of subjective response to glare	Correlation metric	Study I	Study II	Study III
Binary scale	*Point-biserial*	0.27	**-0.40***	0.12
4-point ordinal scale	*Spearman's rank*	0.28	**-0.38***	0.10

In contrast to previous studies, we did not find an influence of macular pigments on discomfort glare sensitivity under neutral daylit conditions. One possible explanation could be that in our three evaluated studies, the glare source was outside the fovea and at 31°to 45° from central line of sight, unlike in previous studies where the sources were within at most 6° of the participants' central line of sight. Additionally, the daylight filtered by neutral glazing in Study I and Study III was of a broad enough spectrum not to be dominated by short wavelength radiation, and this was not the case in most of the previous studies that used a xenon lamp. However, in the case of blue-coloured glazing, we did find a significant effect of MP on glare sensitivity even though the glare source was not falling within the fovea. A possible explanation of this finding relates to the spectral transmission of the glazing used in Study II which had a peak transmission at 440nm (-wavelength region strongly absorbed by MP). This suggests that the influence of MP on glare protection would presumably only be seen when dealing with a glare source dominated by short-wavelength radiation. Another distinguishing factor in our studies was that the participants were free to look around and did not have to fix their gaze, unlike past studies. To delve into this further, we estimated that over the course of each experimental session, the participants' average gaze direction varied from +10 degrees to -15 degrees in vertical plane from their central line of sight. This was derived based on the recording of their faces during the exposure which were then processed in a deep learning model (Baltrusaitis et al., 2018). This gaze behaviour indicates that even though the glare source (sun) was not consistently projected in the fovea, there may have been instances where the sun was closer to the fovea and therefore, resulting in stronger attenuation through the macula.

4 Conclusions and outlook

Overall, the results demonstrate that MPOD cannot account for the inter-individual variability observed in discomfort glare perception for typical work scenarios (i.e., with free gaze behaviour and glare source outside the fovea) under neutral daylight condition, but can, in part, explain the variability when glare is perceived under saturated blue glazing. It is important to further validate these findings, specifically under electrochromic (EC) glazing, which exhibits a blue color and is more commonly used in buildings than the saturated blue glazing used in our experiment. A comparative study conducted by Jain et al., 2022), based on measurements, has shown that the attenuation effect of macular pigment was higher for saturated blue glazing compared to the blue EC glazing, primarily due to the narrower spectral shape of the saturated blue glazing. This suggest that the macular pigments may not have a stronger impact on glare perception under blue EC glazing or less saturated blue glazing. Additionally, this leads to the hypothesis that the spectral power distribution of the light source plays a crucial role in determining the strength of the influence of macular pigments on glare sensitivity, rather than solely relying on the apparent color of the glare source. However, further confirmation through a user study is necessary to validate this hypothesis.

The results from the three presented studies can also be useful for the development of the glare prediction algorithms that aim to model the optical pathways involved. For such a model to enhance the reliability and accuracy, it could be beneficial to incorporate different range of macular pigment density, particularly when dealing with the glare sources that are located close to the fovea and exhibit a dominant emission in the shorter wavelength region. In these specific cases, the variations in macular pigment density among individuals may partially account for the differences observed in glare perception. A first step towards this has already started in the ongoing CIE- Technical Committee 3-57, which focuses on deriving a generic discomfort glare sensation model from a physiological perspective.

Based on our findings, which revealed no impact of MPOD on sensitivity to glare under neutral daylit conditions, it can be hypothesized that MP variations that exist among individuals with a healthy macula do not significantly contribute to the discomfort glare mechanism. Consequently, it provides direction for the future studies to shift their focus towards exploring the visual pathways beyond the pre-receptoral filters in order to gain a deeper understanding of the mechanisms underlying discomfort glare.

Acknowledgments

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. The work is funded by the Swiss National Foundation project (SNF) grant (number 200020_182151) for the project "Visual comfort without borders: interactions on discomfort glare".

References

Baltrusaitis, T., Zadeh, A., Lim, Y. C., & Morency, L.-P. (2018). OpenFace 2.0: Facial Behavior Analysis Toolkit. *2018 13th IEEE International Conference on Automatic Face & Gesture Recognition (FG 2018)*, 59–66. https://doi.org/10.1109/FG.2018.00019

CEN. (2019). *EN17037:2019 Daylight in buildings* (No. EN17037). European Committee for Standardization.

Hammond, B. R., Fletcher, L. M., & Elliott, J. G. (2013). Glare Disability, Photostress Recovery, and Chromatic Contrast: Relation to Macular Pigment and Serum Lutein and Zeaxanthin. *Investigative Opthalmology & Visual Science*, *54*(1), 476. https://doi.org/10.1167/iovs.12-10411

Hemphälä, H., Heiden, M., Lindberg, P., & Nylén, P. (2021). Visual Symptoms and Risk Assessment Using Visual Ergonomics Risk Assessment Method (VERAM). In N. L. Black, W. P. Neumann, & I. Noy (Eds.), *Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021)* (pp. 729–735). Springer International Publishing. https://doi.org/10.1007/978-3-030-74605-6_92

Jain, S., Wienold, J., & Andersen, M. (2022). Comparison between CIE 2° and 10° field photopic luminosity functions V(λ) for calculating daylight discomfort glare metrics. *14th European Lighting Conference (LUX EUROPA)*. LUX EUROPA, Prague, Czech Republic. https://infoscience.epfl.ch/record/296962/files/FInal_Lux_Europa_2022_SJ.pdf

Jain, S., Wienold, J., Lagier, M., Schueler, A., & Andersen, M. (2023). Perceived glare from the sun behind tinted glazing: Comparing blue vs. color-neutral tints. *Building and Environment*, *234*, 110146. https://doi.org/10.1016/j.buildenv.2023.110146

Loughman, J., Akkali, M. C., Beatty, S., Scanlon, G., Davison, P. A., O'Dwyer, V., Cantwell, T., Major, P., Stack, J., & Nolan, J. M. (2010). The relationship between macular pigment and visual performance. *Vision Research*, *50*(13), 1249–1256. https://doi.org/10.1016/j.visres.2010.04.009

Mainster, M. A., & Turner, P. L. (2012). Glare's Causes, Consequences, and Clinical Challenges After a Century of Ophthalmic Study. *American Journal of Ophthalmology*, *153*(4), 587–593. https://doi.org/10.1016/j.ajo.2012.01.008

Osterhaus, W. K. E. (2005). Discomfort glare assessment and prevention for daylight applications in office environments. *Solar Energy*, *79*(2), 140–158. https://doi.org/10.1016/j.solener.2004.11.011

Stringham, J. M., Bovier, E. R., Wong, J. C., & Hammond, B. R., Jr. (2010). The Influence of Dietary Lutein and Zeaxanthin on Visual Performance. *Journal of Food Science*, *75*(1), R24–R29. https://doi.org/10.1111/j.1750-3841.2009.01447.x

Stringham, J. M., Fuld, K., & Wenzel, A. J. (2004). Spatial Properties of Photophobia. *Investigative Opthalmology & Visual Science*, *45*(10), 3838. https://doi.org/10.1167/iovs.04-0038

Stringham, J. M., Garcia, P. V., Smith, P. A., McLin, L. N., & Foutch, B. K. (2011). Macular Pigment and Visual Performance in Glare: Benefits for Photostress Recovery, Disability Glare, and Visual Discomfort. *Investigative Opthalmology & Visual Science*, *52*(10), 7406. https://doi.org/10.1167/iovs.10-6699

Stringham, J. M., & Snodderly, D. M. (2013). Enhancing Performance While Avoiding Damage: A Contribution of Macular Pigment. *Investigative Ophthalmology & Visual Science*, *54*(9), 6298–6306. https://doi.org/10.1167/iovs.13-12365

Wenzel, A. J., Fuld, K., Stringham, J. M., & Curran-Celentano, J. (2006). Macular pigment optical density and photophobia light threshold. *Vision Research*, *46*(28), 4615–4622. https://doi.org/10.1016/j.visres.2006.09.019

Whitehead, A. J., Mares, J. A., & Danis, R. P. (2006). Macular Pigment: A Review of Current Knowledge. *Archives of Ophthalmology*, *124*(7), 1038–1045. https://doi.org/10.1001/archopht.124.7.1038

Wilson, M. R., Sandberg, K. A., & Foutch, B. K. (2021). Macular pigment optical density and visual quality of life. *Journal of Optometry*, *14*(1), 92–99. https://doi.org/10.1016/j.optom.2020.07.008