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.

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.

Figure 1 Participants performing the tasks in blue-tinted glazing (left) and in color-neutral glazing (right)

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

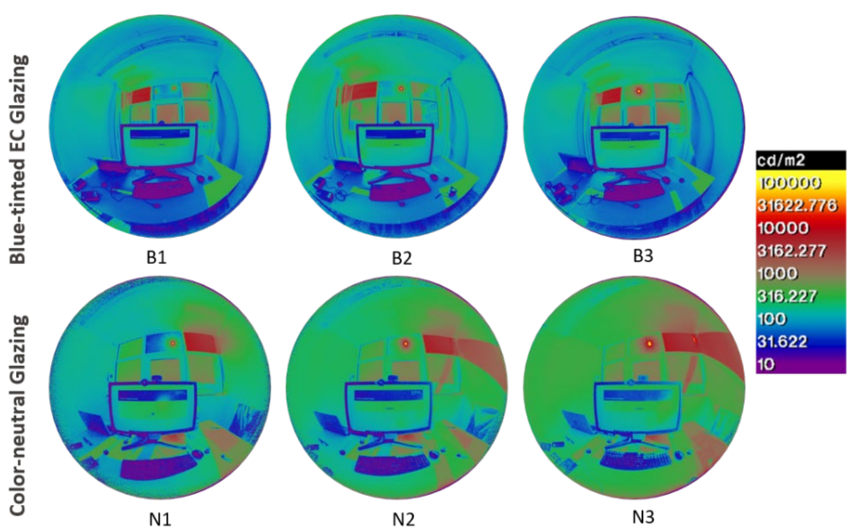

Figure 2 Falsecolor images of the test conditions shown to the participants with changing visible light transmittance of the sun window for blue-tinted and color-neutral glazing

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.

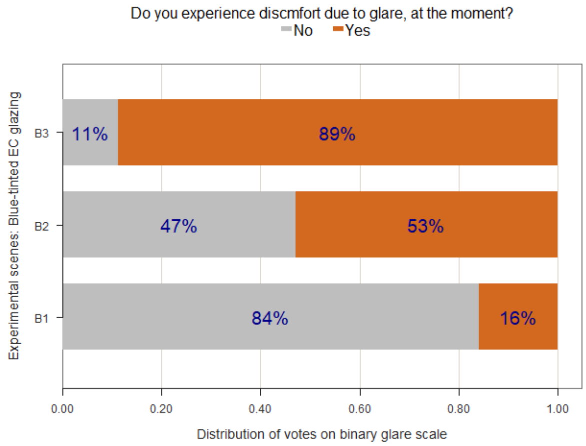

Figure 3 Glare vote distribution under blue-tinted glazing for three different glazing transmittances

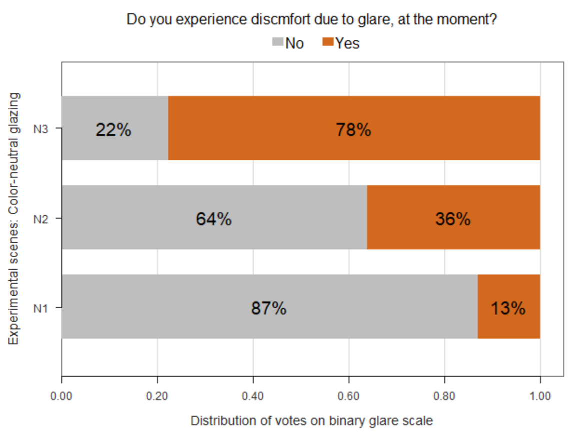

Figure 4 Glare vote distribution under color-neutral glazing for four different glazing transmittances

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.

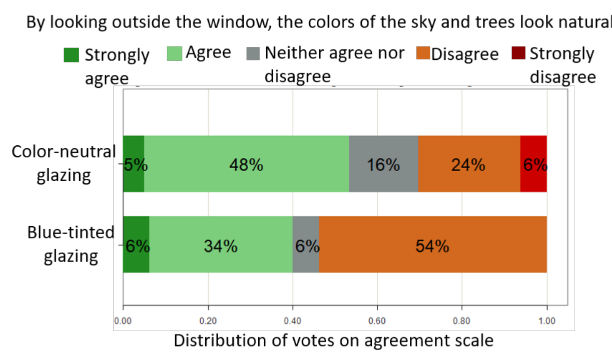

Figure 5 Votes on the color perception of the outdoor environmental elements

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.

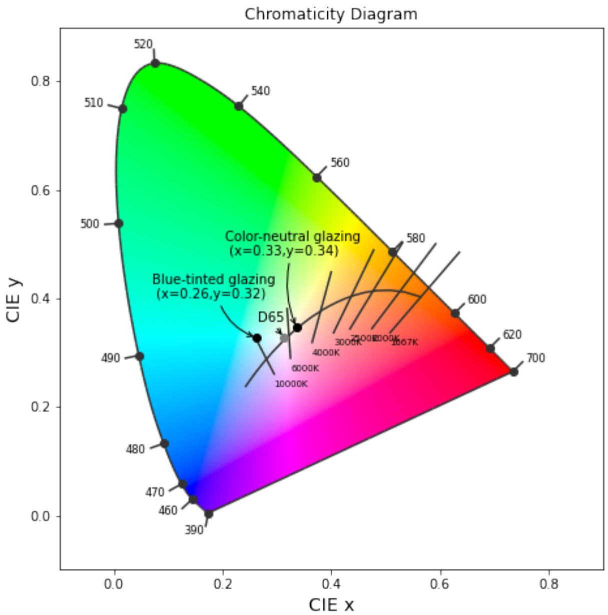

Figure 6 Chromaticity coordinates (x, y) representing the experimental scenarios (mean values) for blue-tinted and color-neutral glazing with the blackbody locus.

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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REFERENCES

[1] A. Piccolo and F. Simone, "Effect of switchable glazing on discomfort glare from windows," *Building and Environment*, vol. 44, no. 6, pp. 1171–1180, Jun. 2009, doi: 10.1016/j.buildenv.2008.08.013.

[2] "Switchable facade technology ('swift') | SWIFT Project | FP5 | CORDIS | European Commission." https://cordis.europa.eu/project/id/ENK6-CT-1999-00012 (accessed Feb. 12, 2021).

[3] R. Baetens, B. P. Jelle, and A. Gustavsen, "Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review," *Solar Energy Materials and Solar Cells*, vol. 94, no. 2, pp. 87–105, Feb. 2010, doi: 10.1016/j.solmat.2009.08.021.

[4] Hh. Arsenault M and M.-C. Dubois, "GLAZING COLOUR TYPES, DAYLIGHT QUALITY, AROUSAL AND SWITCH-ON PATTERNS FOR ELECTRIC LIGHTS".

[5] J. Fekete, C. Sik-Lányi, and J. Schanda, "Spectral discomfort glare sensitivity investigations," *Ophthalmic and Physiological Optics*, vol. 30, no. 2, pp. 182–187, Mar. 2010, doi: 10.1111/j.1475-1313.2009.00696.x.

[6] M. Aries, M. Aarts, and J. van Hoof, "Daylight and health: A review of the evidence and consequences for the built environment," *Lighting Research and Technology*, vol. 47, no. 1, pp. 6–27, Feb. 2015, doi: 10.1177/1477153513509258.

[7] E. S. Lee, E. S. Claybaugh, and M. LaFrance, "End user impacts of automated electrochromic windows in a pilot retrofit application," *Energy and Buildings*, vol. 47, pp. 267–284, Apr. 2012, doi: 10.1016/j.enbuild.2011.12.003.

[8] S. Jain, C. Karmann, and J. Wienold, "Behind electrochromic glazing: Assessing user's perception of glare from the sun in a controlled environment," *Energy and Buildings*, vol. 256, p. 111738, Feb. 2022, doi: 10.1016/j.enbuild.2021.111738.

[9] S. Jain, C. Karmann, and J. Wienold, "Subjective assessment of visual comfort in a daylit workplace with an electrochromic glazed façade," *J. Phys.: Conf. Ser.*, vol. 2042, no. 1, p. 012179, Nov. 2021, doi: 10.1088/1742-6596/2042/1/012179.

[10] J. Mardaljevic, R. Kelly Waskett, and B. Painter, "Neutral daylight illumination with variable transmission glass: Theory and validation," *Lighting Research & Technology*, vol. 48, no. 3, pp. 267–285, May 2016, doi: 10.1177/1477153515620339.

[11] M. Lagier, A. Bertinotti, O. Bouvard, L. Burnier, and A. Schüler, "Optical properties of in vacuo lithiated nanoporous WO3:Mo thin films as determined by spectroscopic ellipsometry," *Optical Materials*, vol. 117, p. 111091, Jul. 2021, doi: 10.1016/j.optmat.2021.111091.

[12] J. Fleury, L. Burnier, and A. Schüler, “Electronic properties and ion migration of ‘in vacuo’ lithiated nanoporous WO3:Mo thin films,” *Journal of Applied Physics*, vol. 131, no. 1, p. 015301, Jan. 2022, doi: 10.1063/5.0074455.
[13] J. Wienold, “Evalglare–A new RADIANCE-based tool to evaluate daylight glare in office spaces,” 2004.
[14] W. K. E. Osterhaus and I. L. Bailey, “Large Area Glare Sources and Their Effect on Discomfort and Visual Performance at computer Workstations,” in *Proceedings of the 1992 IEEE Industry Applications Society Annual Meeting*, Houston, TX, USA, 1992, pp. 1825–1829. doi: 10.1109/Ias.1992.244537.
[15] C. Pierson, “Discomfort glare perception from daylight: influence of the socio-environmental context,” UCL - SST / ILOC - Faculty of Architecture, Architectural Engineering, Town Planning, 2019. [Online]. Available: http://hdl.handle.net/2078.1/222924
[16] G. Chinazzo, “Combined effects of daylight transmitted through coloured glazing and indoor temperature on thermal responses and overall comfort,” *Building and Environment*, p. 15, 2018.
[17] T. Saito and M. Rehmsmeier, “The Precision-Recall Plot Is More Informative than the ROC Plot When Evaluating Binary Classifiers on Imbalanced Datasets,” *PLoS One*, vol. 10, no. 3, p. e0118432, Mar. 2015, doi: 10.1371/journal.pone.0118432.