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

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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 ($\tau_v$) of 0.6% is sufficient to control glare when the sun is in the peripheral field of view (FOV) while $\tau_v,n-n$ 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 ($\tau_v$) 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 façade 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 $\tau_v$ 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 $\tau_v$ 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": $\tau_v$ of the sun window of 1.6% and sun in the participants’ central FOV

ii. "0.6C": $\tau_v$ of the sun window of 0.6% and sun in the participants’ central FOV

iii. "0.6P": $\tau_v$ of the sun window of 0.6% and sun in the participants’ peripheral FOV

iv. "0.14C": $\tau_v$ of the sun window of 0.14% (achieved by installing a removable colour neutral window filter of 22% $\tau_v$ 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% $\tau_v$ in a critical viewing direction. In scene 0.6C, 53% of the participants reported discomfort due to glare which was the lowest $\tau_v$ 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 $\tau_v$ values (0.14%, 0.6% and 1.6%) during four scenarios, another one windowpane at maximum $\tau_v$ 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](https://via.placeholder.com/150)

**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, $\rho_{Spearman}=0.45$). 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 $\tau_v \sim 0.6\%$ 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 $\tau_v$ 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.

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