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INVESTING IN WELL-BEING IN CHALLENGING FUTURE

Effect of Blue-Tinted Glazing on Thermal and Visual Perception in Neutral and Warm Thermal Conditions

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Abstract

Façade properties influence human responses in a multidomain manner and these interactions needs to be accounted for effective façades design, particularly to increase resilience to extreme heat. From existing research, it remains unclear whether the glazing colour properties can influence occupant thermal sensation, preferences, and acceptance, or whether higher temperatures affect glare sensation or view perception. This study investigates the combined influence of tinted glazing in façades through a preliminary experimental campaign with human participants exposed to varying glazing hues (neutral and blue) and indoor air temperatures. While previous research has examined the impact of coloured daylight on thermal and glare sensation under thermal conditions close to neutrality, this paper compares occupant responses at neutral and warm thermal conditions by performing repeated measurements.

An experiment was conducted to measure potential differences in human thermal sensation, acceptance, preference, and glare sensation under two thermal conditions (operative temperatures of 25°C and 30°C) and two daylight colours (neutral and blue). Thirty-nine participants were exposed to different combinations of temperature and glazing colour in a randomized order. Data were collected using questionnaires and thermal physiological sensors to capture human responses to these varying conditions. In terms of visual perception, the results demonstrate a distinction between the two visual scenarios, particularly regarding obstruction and glare at a neutral temperature. At the level of thermal sensation, the impact of blue-tinted glazing is not statistically significant with this number of participants. However, a slight difference is observed between the two scenarios at both temperature levels.

Keywords

thermal acceptance, human multi-domain comfort, tinted glazing, visual comfort

1. Introduction

Windows and transparent facades are a pivotal yet complex component in architectural design, with far-reaching implications for energy efficiency, overall comfort, and the aesthetic appeal of buildings. Significant research has demonstrated the benefits of natural light on human health and well-being *(Knoop, 2020)*. Empirical evidence also indicates that exposure to natural light plays a pivotal role in regulating circadian rhythms, with beneficial effects on sleep, mood and work performance *(Li, 2024)*. The presence of outdoor views, particularly those incorporating natural elements, has been demonstrated to be an effective means of reducing stress and enhancing occupant satisfaction, thereby contributing to the creation of a healthier and more pleasant environment. For instance, several studies conducted within educational settings have indicated that students perform better on the same test when it is taken in a sunny environment rather than one with artificial lighting *(Bernardi, 2006)*. In the context of the workplace, research has indicated that natural lighting and access to outdoor views can lead to an increase in employee productivity. These factors are closely associated with an improvement in the overall well-being of occupants, with a positive impact on physical and mental health and higher levels of satisfaction. Korance *(Korance, 2021)* demonstrated that access to daylight access can enhance performance, and additionally identified a statistically significant correlation between outdoor view access and workers' stress levels. Nevertheless, while glazing transparent components offers numerous advantages, it can also result in severe discomfort, particularly in relation to thermal and glare issues.

Balancing the competing influences of transparent facades (enhancement of well-being and health by access to daylight and view versus glare or overheating) has been the objective of current high-performance windows and facades by providing means for the optimal control of solar radiation *(Turan, 2020)*. This is particularly relevant in the context of climate change, where global warming is increasing the need for effective passive design strategies for reducing indoor overheating. However, the attempt of controlling solar radiation to reduce overheating risk can significantly reduce window-to-wall ratios and overall access to natural daylight. For this reason, the dynamic control of solar radiation by advanced fenestration strategies is promising since it can maintain high transparency while dynamically controlling the solar radiation to reduce heat gains only when required, thus balancing competing comfort requirements *(Luna-Navarro, 2022)*. One of the most promising technologies is switchable electrochromic (EC) glazing, which enables the user to modify the desired level of light and solar transmission *(Michael, 2023)*. This approach effectively reduces glare while maintaining view out, thus improving visual and thermal comfort and buildings' energy performance without compromising the quality of the indoor environment *(Lee, 2007; Mardaljievic, 2013)*. In recent years, numerous studies have aimed to evaluate the potential of EC glazing in enhancing occupant comfort. However, commercially available EC glazing materials tend to exhibit a spectral shift towards shorter wavelengths in their darkened state, resulting in a blue hue that distorts the natural light spectrum. Despite this, there has been little research into how this spectral shift affects occupants' visual and glare perception, or the broader impact of tinted glazing. Previous studies on glare perception under electric lighting, particularly with LED sources, have shown that coloured lighting can significantly increase discomfort from glare, with blue light being associated with the highest levels of discomfort *(Baetens, 2010)*. Considering the distinct spectral properties of blue-tinted electric light compared to daylight transmitted through electrochromic glass, Jain et al. *(Jain, 2023)* conducted a study to assess the influence of blue-tinted glazing on glare perception when the sun is within the field of view. Their findings indicated that participants reported glare more frequently with blue-tinted glazing compared to neutral-tinted one, even though measured glare levels were higher with the neutral-tinted glass.

Concurrently, the Hue-Heat Hypothesis is evolving, which posits a significant influence of daylight or light colour on individuals' thermal perception *(Bennet, 1972)*. Research has demonstrated that long-wavelength colours, such as red, are associated with a sensation of warmth, whereas short-wavelength colours, such as blue, evoke a feeling of coolness. Kaya et al. *(Kaya, 2004)* identified the relationship between colour and sensory experience for the first time, thereby deepening the understanding of this phenomenon. Based on this, several studies were conducted in which participants consistently reported feeling warmer in rooms illuminated by red light compared to those lit by blue light, despite the actual temperatures being identical *(Huebner, 2016; Haiying, 2018; Luo, 2023)*.

This phenomenon suggests that the incorporation of tinted glass into architectural design may have the potential to influence the perceived temperature of interior spaces. In this regard, the study conducted by Chinazzo et al. *(Chinazzo, 2018)* corroborates the hypothesis that coloured daylight influences people's thermal response, irrespective of the actual room temperature. In particular, the study demonstrated that the subjective psychological thermal response, under neutral and near-neutral conditions, is significantly affected by coloured daylight, while no physiological effect was observed. However, no previous study investigated if these effects are still present under warmer thermal condition, much further from neutral.

To this aim, we conducted experiments with participants to evaluate whether daylight transmitted through tinted glazing can also influence aspects of visual satisfaction (i.e. perception of view, daylight access and glare) and thermal perception when occupants are exposed to warm thermal conditions. The aim of this experimental campaign was therefore to study the combined effects of blue-tinted glazing and indoor temperature on participants thermal and visual perception under thermal conditions far from neutrality.

2. Materials and methods

This study is based on laboratory tests conducted in two semi-controlled rooms with monitored temperature and daylight transmitted through tinted glazing. The objective was to assess whether there was an impact of shorter daylight wavelengths (e.g. blue) on the participants' sensation, particularly visual and thermal, compared to a neutral daylight reference, and whether this effect is also present under warm thermal conditions.

2.1. Design of the experiment

The combined effect of coloured daylight and air temperature on thermal response and visual response was investigated using a 2 x 2 experimental design, which conditions are described in Table 1. Based on calculations conducted with the CBE Comfort Tool *(Tartarini, 2020)*, two temperature levels were identified: a neutral condition of 25°C, which was adopted as a reference, and a warm condition of 30°C. These calculations were based on a clothing level of 0.61 clo (summer) and a metabolic rate of 1 MET. Regarding the spectral composition of the daylight, two alternatives were selected, based on colours exhibited by existing dynamic glazing technologies: blue and neutral (shown in Figure 1 and Figure 2).

Table 1. Description of the scenarios investigated during the experimental campaign

Scenario	Operative temperature	Window film colour
1	25	Neutral
2	25	Blue
3	30	Neutral
4	30	Blue

In order to achieve the desired chromatic effect, films were fixed to acrylic panels positioned on the windows of the two test rooms in front of triple glass. Although the films differed in their colour rendering properties, they were selected to result in similar visible transmittance characteristics, with values of 50% for blue and 51.2% for neutral. Following the application of the filters, a preliminary characterization was conducted using spectrophotometric measurements, which enabled the collection of data on the colour of the daylight filtered by the glazing treated with the coloured films.

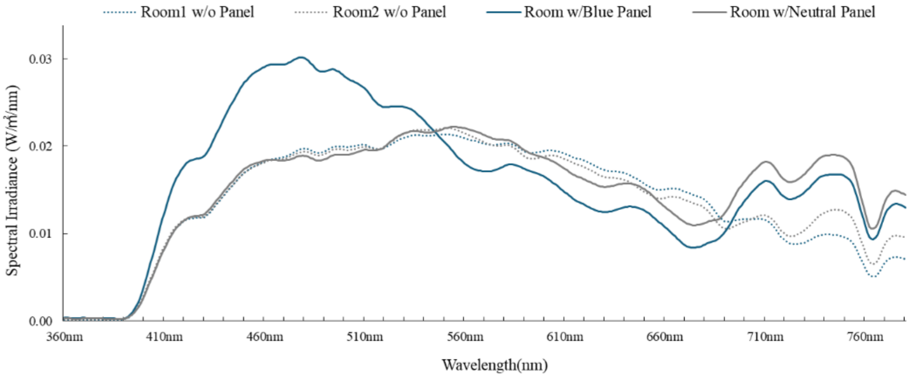


Figure 1: Spectral irradiance distribution

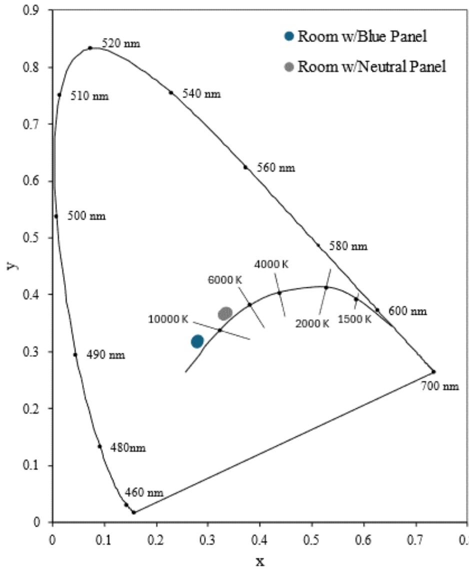


Figure 2: Chromaticity coordinates (x,y) of the experimental conditions

As illustrated in Figure **1**, the radiation spectrum of the blue film exhibits a peak at 478 nm, while the neutral films display a peak at 555 nm, which is approximately the same value observed in the glazing without a film applied (i.e. 551 nm).

Figure 2 illustrates that the distance to the Planckian locus *(Ohno, 2014)* curve is minimal and similar for both films, suggesting that transmitted daylight appears as a "white" coloured light to the human eye, although they exhibit different correlated colour temperature. Consequently, the two-coloured daylight conditions are comparable and far from saturated colour levels, allowing the impact of the blue film on human perception to be assessed against the neutral reference. Subsequently, simulations were conducted in ClimateStudio to analyse the sun path and determine the position of the sun in relation to the windows. Following a comprehensive analysis, the time slot from

2pm to 4pm was selected, as the sun was not visible in the field of view during this interval, to assess diffuse glare.

2.2. Experiment and monitoring setup

The experimental campaign was conducted between June and August 2024 within the MOR pavilion, situated within the Green Village on the campus of Delft University of Technology (The Netherlands, Cfb Köppen-Geiger climate class *(Kottek, 2006)*). The Green Village is a living laboratory, in which a variety of building prototypes are tested with the occupants who work and live in them.

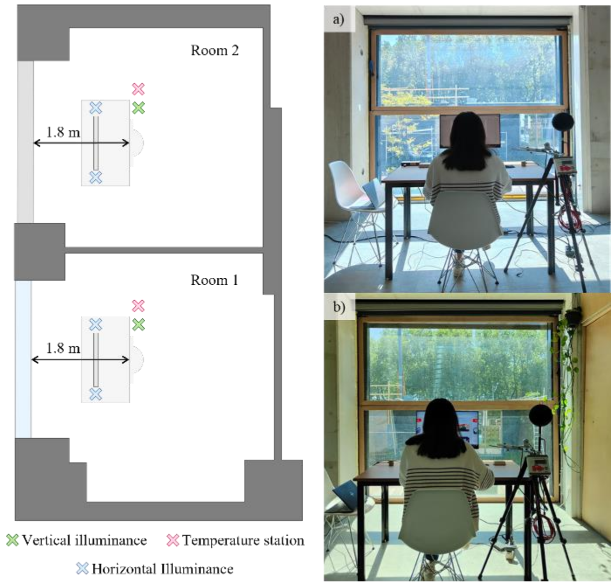


Figure 3: Plan of room configuration, together with sensors position, and view of the test rooms' façade with blue (a) and neutral (b) film applied

Two adjacent rooms of similar dimensions at the MOR building were used for the experiment. Each room has a south-west-facing opening, fitted with the same type of triple glass, with identical characteristics and properties (Tvis = 73%), and framed by metal frames. Acrylic panels with tinted films were positioned in front of the windows: the first room was equipped with blue-tinted film (Figure 3-a), while the second room was equipped with neutral one (Figure 3-b).

In both rooms, heating and cooling were provided by the mechanical ventilation system integrated in the MOR pavilion, positioned in the false ceiling. Each room was equipped with a desk and a workstation, where participants were invited to perform their reading task.

The workstation consisted solely of a monitor and mouse, with the keyboard removed to prevent participants from looking away from the screen. This was done to ensure that participants maintained a constant eye-level height, eliminating any fluctuation between the screen and keyboard. Both rooms were furnished with the instruments for the continuous monitoring of indoor environmental parameters, with a sampling rate of one minute.

Table 2 provides a summary of the technical characteristics of all the sensors employed in the study. To obtain data on environmental conditions, a temperature station was installed at a distance of approximately 0.5 meters from the participant, at eye level. This comprised a globe thermometer and a temperature sensor for the measurement of mean radiant temperature and air temperature, in addition to a vertically positioned luxmeter for the assessment of vertical illuminance level (Figure **4**). Furthermore, two luxmeters were positioned on the desk, to the right and left of the supplied monitor, in order to assess the horizontal illuminance level. One of these is integrated into the HOBO datalogger, which also permits collection of relative humidity data. Finally, glare levels were characterised by collecting vertical illuminance and Daylight Glare Probability (DGP) values using a Konica Minolta illuminance meter (model T-

10A) and an LMK Mobile Advanced luminance camera (model Canon EOS 350D) equipped with a Sigma fisheye lens. The equipment, solely at certain phases of the experimental procedure, was placed in the exact position of the participant in order to evaluate the subject's visual conditions. Furthermore, as detailed in Table **2**, physiological data was gathered, which, however, will be not presented in this publication.

Table 2: Specifics of sensors used in the experiment

Signal		Sensor Name	Parameter	Sensor Accuracy
Environmental	1	Globe Thermometer	Mean Radiant Temperature [°C]	±0.1°C
	2	Pt100	Air Temperature [°C]	±0.1°C
	3	Luxmeter	Illuminance [lx]	Resolution 3 lx
	4	Hobo MX1104	Air Temperature [°C]	±0.2°C
			Relative Humidity [%]	±3.5%
			Illuminance [lx]	±10%
Physiological	5	Garmin Venu2 Smartwatch	Heart Rate [Hz]	-
	6	iButton	Skin Temperature [°C]	±1.0°C

Figure 4: Setup of the experiment (number refers to the list of Table 2) and luminance measurements equipment

2.3. Participants

Ethics approval for this research was obtained from TU Delft’s Human Research Ethics Committee. A total of 39 volunteers participated in the experiment, of whom 49% were women. The participants, with an average age of 29.2 ± 3.4 years, were recruited at the university campus, including students, lecturers and members of Green Village staff, through the administration of an invitation questionnaire. In order to participate in the study, individuals were required to meet specific criteria, including being in good health, having a Body Mass Index (BMI) within the normal range, and not using drugs or consuming excess alcohol. Additionally, participants were asked to indicate via an initial questionnaire whether they had normal or corrected vision, to ensure that any visual deficits would not affect their performance.

During the experimental session, participants were required to complete a low impact reading task (metabolic rate: 1 MET) at the provided workstation. In the simulations conducted with the CBE Comfort Tool, a thermal insulation value of 0.61 clo was assumed, corresponding to the typical clothing ensemble of a long-sleeved shirt and long trousers. However, participants were not required to wear specific clothing items, but were instructed to maintain the type of clothing worn throughout the session. Based on the analysis of the participants' responses to the introductory questionnaire, a clothing index was calculated to be equal to 0.48 ± 0.08.

2.4. Experimental procedure

The experimental procedure requires subjects to participate in the experiment on two separate days, in order to test both thermal scenarios, namely neutral and warm. Each test day is scheduled to take place during the designated time slot (2pm-4pm) and comprises two experimental sessions, each lasting for an hour. Each session is divided into three phases: a preliminary phase, during which the subjects are adapted to the indoor environmental conditions and the experimental procedure is explained; and two experimental phases. During the preliminary phase, participants are also asked to complete an introductory questionnaire, which gathers demographic information, their current physical state, and data pertaining to their thermal, visual, and colour sensitivity.

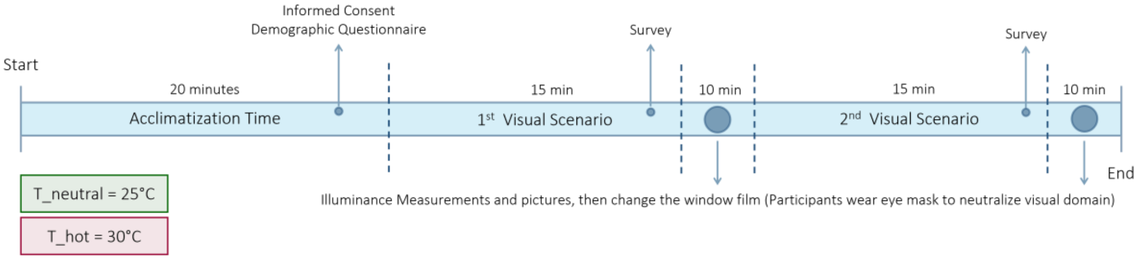


Figure 5: Experimental procedure

Subsequently, the participants were separated and each assigned to a starting room with blue-tinted or neutral glazing. To ensure comparability between the two experimental days of each subject, the starting condition of the coloured daylight was maintained throughout both experimental days. The two main phases, each lasting 15 minutes, required the participant to experience both visual scenarios in sequence. During each phase, participants performed a reading task and, midway through each phase, completed a questionnaire to assess the thermal, visual and colour conditions of the room.

A ten-minute break was observed between the two phases, during which the researcher conducted glare measurements utilizing a luminance camera and illuminance meter. During this interval, participants were instructed to wear an eye mask to neutralize visual stimuli. At the conclusion of the intermission, participants relocated to the other experimental room to experience the alternative visual scenario.

2.5. Statistical analysis

The differences between the experimental scenario were analysed for significance with linear mixed methods by using the *lmer* library. The number or participants for significance was decided by considering the ANOVA repeated measures test and “moderate” as effect size. A p-value of 0.05 was considered for the threshold of significance. A total number of 30 participants was deemed sufficient by this analysis, but we decided to increase the number of participants for redundancy in case a few experimental sessions had to be removed.

3. Results

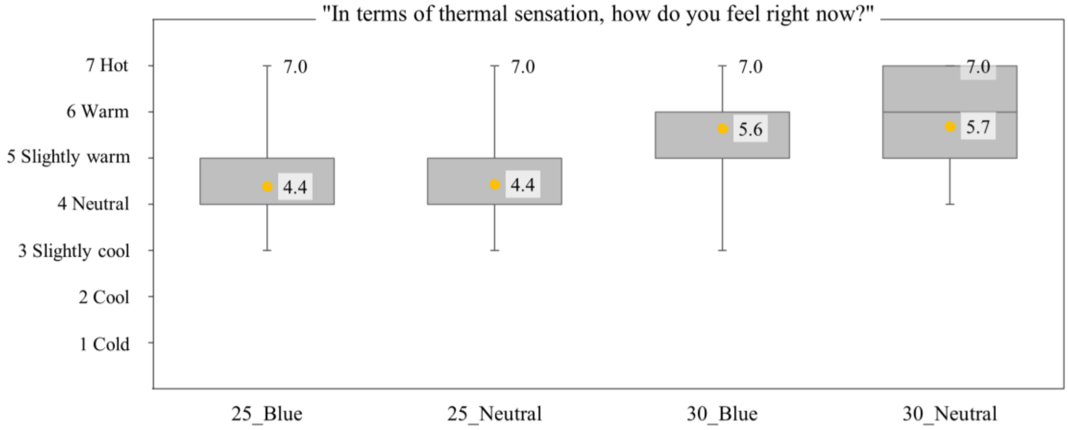
3.1. Overview of environmental data

The environmental data collected showed that the experimental conditions were similar to the desired experimental conditions of the design. For each scenario, it was observed that the average temperature recorded under neutral conditions was 25.6 ± 1.3°C and 25.6 ± 1.4°C with the blue and neutral panels, respectively, and therefore the two rooms had comparable and identical thermal conditions. Similarly, in the context of warm thermal conditions, the recorded mean temperature was 29.6 ºC ± 1.0 and 29.5 ºC ± 1.2 in both visual scenarios, respectively. Therefore, the recorded temperatures differed only slightly from those predicted in the experimental design, which were 25 ºC and 30 ºC in neutral and warm conditions, respectively. The relative humidity values were also within the design ones, maintaining an average of 50% ± 3.5%.

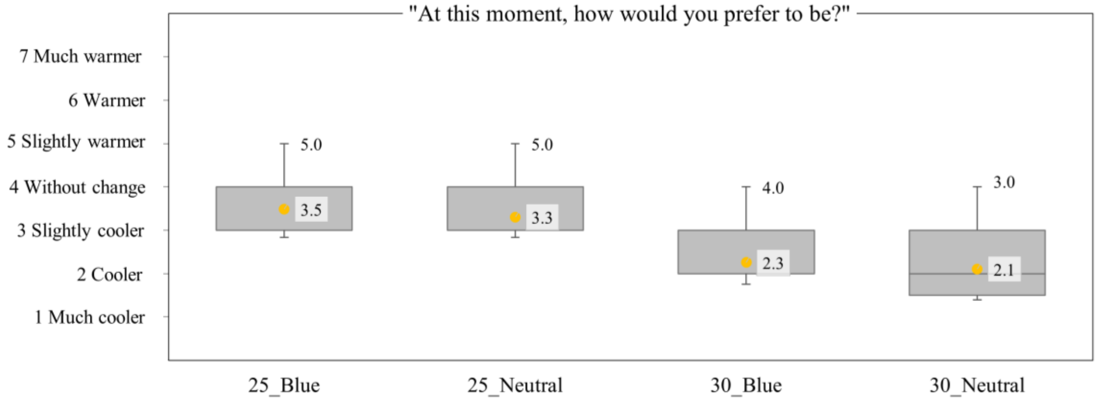
As the experimental sessions were not confined to days with clear skies, but also took place under overcast conditions, the recorded illuminance levels exhibited greater variability. This is due to the fact that daylight levels can fluctuate rapidly depending on the sky and weather conditions. Consequently, both horizontal and vertical illuminance levels were considered as a variable in the statistical analyses conducted. However, all scenarios reported similar ranges, with median values of approximately 1200 lx for vertical and 700 lx for horizontal.

3.2. Thermal responses

In terms of participants' thermal preference, acceptability and sensation, overall, with this number of participants, no significant differences were observed between the two daylight colour scenarios with respect to the first two factors. However, a slight difference emerged between the two scenarios in warm conditions with regard to thermal sensation, as illustrated in the Figure 6-b. This difference proved to be minimal and imperceptible.



(a)



(b)

Figure 6: Thermal Sensation (a) and Thermal Preference (b) evaluation expressed by participants

In addition, in the final questionnaire conducted at the end of each experimental day, in which participants were asked to evaluate to compare the thermal and visual scenarios between the two rooms, 50% of the participants indicated that they perceived the temperature differently in the two visual scenarios, of which the 64% indicated that the room with the neutral panels was perceived warmer than the one with the blue panels.

3.3. Comparison of visual perception under blue and neutral glazing

Firstly, an analysis of glare perception was conducted. The objective assessment of glare was conducted through the measurements made with the illuminance meter and luminance camera, as detailed in section 2.2. Furthermore, a subjective assessment was conducted through the analysis of the responses provided by the participants in the questionnaire. The objective measurements indicated that in all the experimental sessions the DGP was below 0.35 and therefore glare was not perceptible. However, in a small number of sessions (19 out of 156, the 12%), participants reported to experience glare and, in particular, the 63% of the glare conditions were reported in the blue-tinted glazing scenario. However, since the number of sessions that reported glare is small compared to the total number of sessions, we decided to not test this sample for significance.

A significant difference between participants’ responses was observed for other visual factors, namely the perceived level of light in the room (Figure **7**), the perceived view clarity and colour of the view through the window (Figure 8). As shown in the Figure 7, in both conditions, participants in the room with neutral colour glazing reported to perceived the room slightly dark and, in particular, this was significance for the neutral conditions (p-value of 0.004).

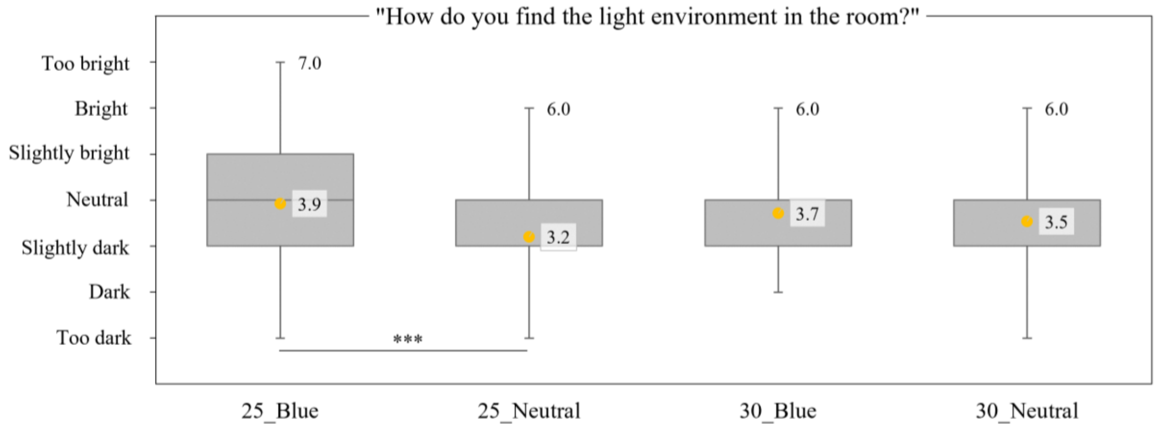
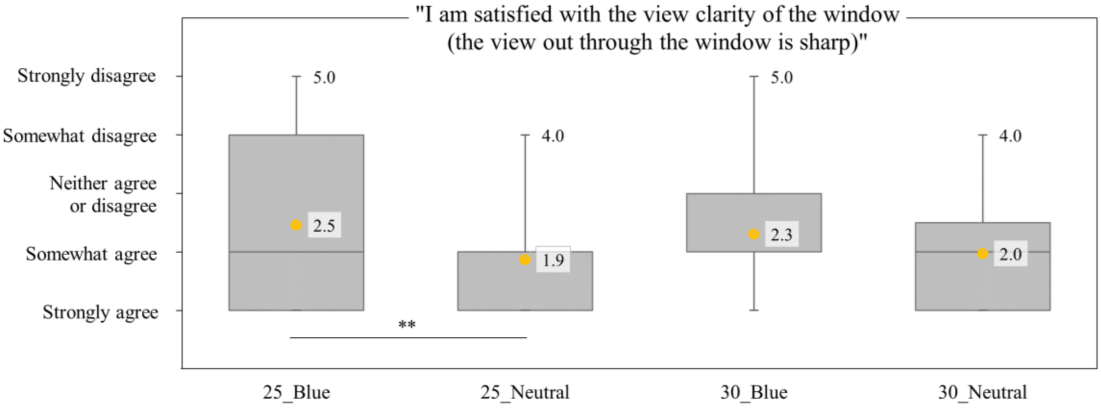
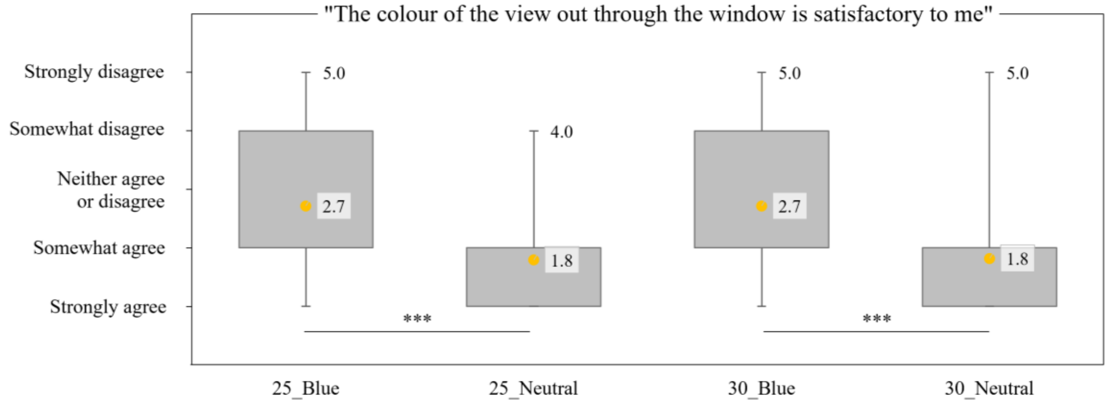


Figure 7: Visual Sensation evaluation expressed by the participants. Significant effect of coloured daylight with “*” p<0.05, “**” p<0.01 and “***” p<0.005.

Overall, as illustrated in Figure 8, participants expressed higher satisfaction with view clarity and view colour during the scenarios where the glazing was neutral (no colour shift). For the satisfaction with the view clarity, we observed a statistically significant difference only for the neutral thermal conditions (p-value of 0.009). For the satisfaction with the colour of the view through the window (Figure 8-b), we observed a statistically significant difference between the two rooms at both thermal conditions (p-values of 1.94×10^{-5} at the neutral thermal conditions and 3.36×10^{-5} at the warm thermal conditions).



(a)



(b)

Figure 8: Sensation of view clarity and colour expressed by participants. Significant effect of coloured daylight with “*” $p<0.05$, “**” $p<0.01$ and “***” $p<0.005$

4. Discussion and conclusions

We designed this study to test if there was moderate or large interaction effect between the visual and the thermal domain at warm and neutral thermal conditions, and under a neutral or blue-tinted glazing. For this reason, a total of 39 participants were recruited to evaluate this. Overall, the visual perception was significantly influenced only by the colour of the glazing, while the thermal perception only by the temperatures in the rooms with few exceptions. With this sample size, we only observed an interaction effect on how participants perceived the overall light environment (bright or dark). Participants reported to perceive the space slightly dark when in the neutral glazing room, despite similar levels of vertical and horizontal illuminance between the two rooms and overall high levels of illuminance (average of 1250 lx for the horizontal illuminance). However, this was only significantly different for the neutral thermal conditions, thus indicating an interaction with temperature. This could be explained by the fact that when participants feel warm may prefer less bright space, however further investigations are required to test this casuality. For instance, we suggest conducting an experimental test where participants are exposed to much larger variance in illuminance levels at cold, neutral and warm conditions to validate further this hypothesis.

In terms of thermal preferences, there is a slightly difference between the two room conditions, and this difference becomes less pronounced when the temperature increases. However, this difference is not significant with this sample size, indicating that there is not a moderate or large effect, but we cannot exclude there may be a small effect, which would require a much larger sample size (e.g. 80 participants). This would be consistent with previous work *(Chinazzo et al, 2018)* and this would explain the responses that the participants reported in the final survey, where a good proportion of participants reported to perceive the room with the blue-tinted glazing cooler than the neutral one. To conclude, the impact of tinted films on thermal perception, in accordance with the hue-heat hypothesis, is negligible. However, they may offer a supplementary means of assessing thermal conditions, particularly when there is a slight deviation from standard levels, resulting in greater energy savings than previously assumed in studies based on coloured artificial light.

From the perspective of visual perception, the findings are consistent with those previously documented in the literature and in the study conducted by Jain et al. *(Jain, 2023)*. The use of blue glazing has been observed to enhance the perceived brightness of an environment, and in some instances, it may elicit a sensation of glare. However, we suggest conducting studies where the indirect or diffuse light is brighter and therefore the probability of glare higher.
Overall, the participants expressed greater satisfaction with the neutral film than with the blue one, in terms of both the colour of the external view and clarity. Nevertheless, we propose conducting experimental sessions in which the occupants do not face the window. This approach may mitigate the impact of the blue-coloured window on visual perception, while allowing for a more comprehensive assessment of the influence of the coloured-light reflection on thermal perception. However, in consistency with previous works, participants did not express dissatisfaction. Therefore, the utilisation of advanced glazing for solar control that present a slight shift towards the blue colour should be acceptable to participants.

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