Variation in thermal, visual and overall comfort evaluation under coloured glazing at different temperature levels

Giorgia Chinazzo* Jan Wienold and Marilyne Andersen

Laboratory of Integrated Performance in Design, School of Architecture, Civil and Environmental Engineering (ENAC), École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland
Email: giorgia.chinazzo@epfl.ch*

Within the scope of a broader research project about daylight and temperature interaction effects on human responses, this paper investigates how daylight transmitted through spectrally selective glazing (blue, orange and a reference neutral) affects thermal comfort of occupants (cross-modal effect of daylight colour), besides the more conventional visual comfort. Similarly, the effect of indoor thermal conditions on the visual comfort evaluation of the transmitted daylight is investigated (cross-modal effect of temperature), as well as that of the combined effect of daylight and temperature on overall comfort. To this end, different analyses are conducted on the dataset collected through experimental investigations in an office-like test room involving a total of 75 participants. Three main conclusions can be drawn from the results of this work: (i) Symmetrical cross-modal effects occur between daylight colour (i.e., daylight transmitted through spectrally selective glazing) and temperature. (ii) Differences in overall comfort evaluations under both blue and orange glazing in comparison with those under the reference glazing are larger in a thermally uncomfortable environment compared to other more comfortable thermal conditions. (iii) Results of spearman correlations show that overall comfort is positively and equally correlated with both visual and thermal comfort evaluations. Based on these results, it can be stated that in the presence of glazing with a colour tint, thermal perception evaluations should be investigated together with the most common visual ones. Moreover, thermal conditions should be considered in parallel with visual ones as visual and overall comfort might be affected by their combined presence.

Received 10 December 2018; accepted 20 December 2018
Published online: 15 March 2019

Introduction

Colour is an essential aspect of the built environment that characterises the entire indoor ambiance, from small objects to the permeating light. Its presence influences occupants' perception and impressions of the indoor space as well as their mood and well-being [1].

The colour of light has been proven to affect visual perception and visual task performance [2], but also to influence other aspects, not directly related to the visual environment. In particular, electric light with different correlated colour temperatures or saturated hues has been reported to affect occupant thermal perception [3-5]. The specific cross-modal effect of coloured lights on human thermal perception is referred to as the "hue-heat-hypothesis" (HHH) [6] and has gained attention for building design and operation due to the fascinating idea of heating and cooling with colours. In fact, according to the HHH, the thermal perception of buildings' occupants could be affected by the presence of coloured lights: lights with a spectrum characterised by longer wavelengths (i.e., reddish) may result in a warmer perception and those with a spectrum characterised by shorter wavelengths (i.e., bluish) in a colder perception. In indoor spaces, one can either have access to electric light (used in past HHH studies) or to natural light (i.e., daylight) – often to both. Hence indoor light will depend on the "colour" of daylight, which will be the result of both direct sunlight and diffuse skylight, will vary in spectrum according to weather, time of the day and season [7-8], and will be strongly dependent on the chosen window's spectral transmittance properties. All glazing types affect the spectrum of the incoming light, filtering out some of its wavelengths. However, most glazing types installed in buildings aim to be "colour neutral" and typically alter the incoming daylight's spectrum only slightly. This is not the case with some new glazing technologies such as electrochromic glazing or dye sensitised solar cells, which result in a coloured appearance of the glazing and of the incoming daylight. These kinds of "smart" glazing options have been investigated to test their impact on the indoor visual environment (e.g., colour rendering performance [9-11]) and on the visual perception of occupants [12-14]. However, with reference to the HHH, the role of a glazing's spectrally selective properties and the resulting transmitted daylight (from now on referred to as "coloured daylight") is an important factor to study for understanding not only the visual perception of the indoor environment, but also of the thermal perception of people as this would result in a cross-modal effect of coloured daylight on thermal perception. Moreover, the perception of the visual appearance of such glazing has never been investigated with reference to indoor thermal conditions, although it could be affected by cross-modal effects of temperature on visual perception.

The present study is a part of a larger research project aiming to understand the interactions between daylight and temperature on human responses, intended as a combination of subjective perception evaluations and physiological response [15]. This broader research focuses amongst others on interactions between coloured daylight and temperature: visual and thermal interactions are investigated by means of experiments in a controlled environment that allows to set, change and monitor the indoor temperature and the coloured daylight through the use of coloured glazing. The already established findings about the effect of coloured daylight on thermal response and the effect of temperature on visual perception can be found in Chinazzo *et al*. [16-17].

This paper focuses on comfort evaluation only, analysing thermal, visual and overall comfort together. Comfort is considered as a specific human response, i.e. as a sub-category of subjective perception. It is specifically an evaluation of the sensation linked to the stimuli generated by the indoor environment [18]. Three main analyses are conducted. The first refers to the comfort evaluation differences between responses recorded under a coloured glazing (blue or orange) with reference to those reported under the reference neutral glazing. The second deals with comfort vote variations between the two colours (blue and orange). Finally, correlations between the three types of comfort are reported in the last analysis. The aim of the two first analyses is to investigate cross-modal effects between coloured daylight and temperature. More specifically, the question is whether the change of glazing, other than affecting visual comfort, has an impact on thermal comfort (cross-modal effect of coloured daylight). Then, as variations are studied at three temperature levels, we also investigate whether the thermal environment plays a role in the visual evaluation (cross-modal effect of temperature) and how the combination of both coloured glazing and temperature levels affects overall comfort. “Coloured daylight” as well as “coloured glazing” will be used interchangeably in the following sections.

Methodology

An experiment was conducted involving the presence of 75 participants, combining different levels of indoor temperature and coloured glazing. The experiment took place in an office-like test room, with controllable indoor temperature by means of a radiant system installed on all opaque surfaces. Details about the test room and the experimental procedure are described in Chinazzo *et al*. [17]. All participants experienced three types of glazing, two coloured (blue and orange) and a neutral one, presented in a randomised order across participants (Figure 1). Each person was exposed to only one of the three temperature levels investigated (19°C, 22°C or 26°C). The experimental session lasted three hours, during which two participants at a time experienced each colour condition for 30 minutes (considered to be a short exposure time), while exposed to the same temperature range for the entire experiment. Thermal adaptation occurred in the first part of the experiment, when participants were exposed to electric light for 45 minutes. In this adaptation phase, a blackout curtain blocked daylight from entering the room.

As already mentioned, the study investigated different human perception evaluations, among which comfort was included. Participants reported their subjective evaluations about thermal, visual and overall comfort on the same five-point semantic differential scale (from very uncomfortable to very comfortable) at the end of each colour exposure (Table 1). Two types of visual comfort questions were included in the investigation, referring respectively to the evaluation of the colour of the light and the general visual environment. We will refer to them as “colour comfort” and “general visual comfort”, respectively. “Thermal comfort” and “overall comfort” will be used to indicate the other two evaluations.

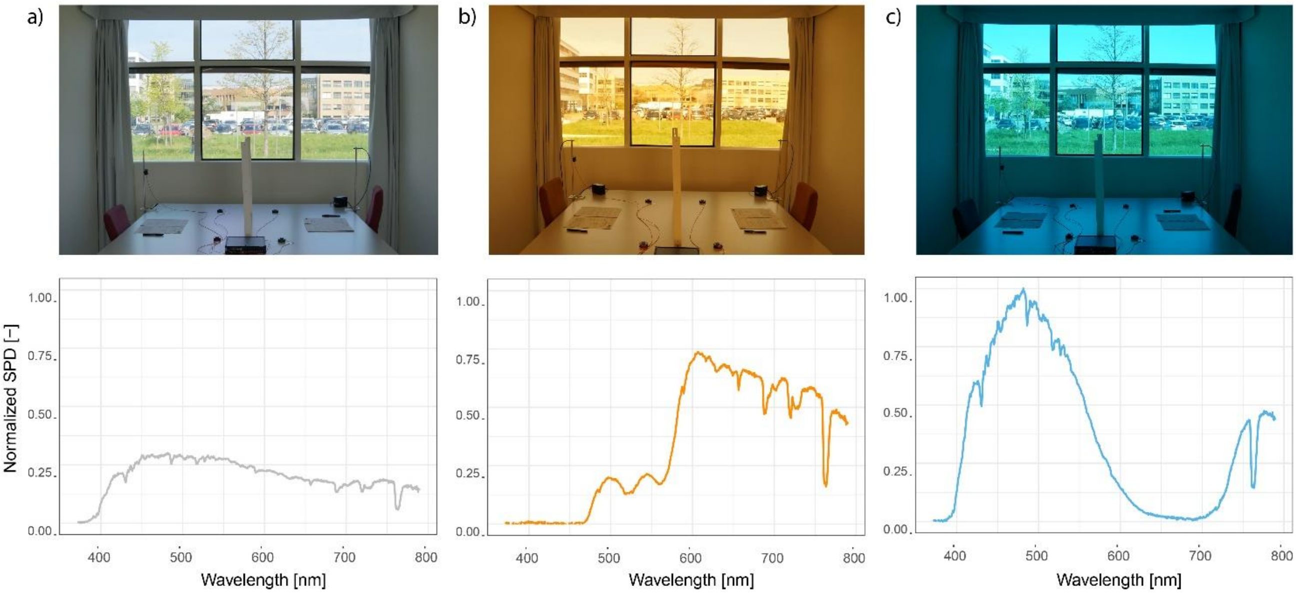

Figure 1: Coloured glazing types used in the experiment (picture of the interior of the test room and normalised relative spectral power distribution): (a) neutral, (b) orange and (c) blue conditions.

	Question	Response scale
Thermal comfort	With reference to how you (thermally) feel in this moment, you find it...	very comfortable (5) comfortable (4) slightly uncomfortable (3) uncomfortable (2) very uncomfortable (1)
Overall comfort	How do you judge the global indoor environment (considering light, temperature, noise and air quality)?	
Colour comfort	How do you find the colour of the light in this room?	
General visual comfort	How do you find the general visual environment in the room?	

Table 1: Thermal, overall and visual (colour and general) comfort questions.

Results and discussion

This section reports and discusses results according to the three types of analyses performed. First, differences in comfort votes under each of the two coloured glazing types in comparison with the neutral one are reported (neutral-colour comfort variation). Then an analysis of the differences in comfort votes between the blue and the orange glazing is described (blue-orange comfort variation). Finally, correlations between the three types of comfort are presented.

Differences in comfort votes under coloured glazing in comparison to neutral glazing

In the experimental design followed for the investigation, the coloured glazing was a within-subject parameter as all participants were exposed to the three types of glazing in a consecutive order, randomised across participants. As a consequence, it is possible to calculate the difference in comfort votes between each of the two coloured glazing types and the neutral one, considered as a reference as the visible transmittance was similar. This difference in comfort votes will be called "neutral-colour comfort variation" and is calculated subtracting the comfort vote under the neutral glazing with that under the blue or the orange glazing. Figure 2 illustrates the neutral-colour comfort variation for the four types of comfort evaluations (Table 1). Considering the linear scale used for comfort evaluation from 1 (very uncomfortable) to 5 (very comfortable), the maximum difference between the two votes is 4. A positive value of the neutral-colour comfort variation indicates that the comfort under the neutral exposure was rated more positively than under the blue or the orange glazing. The opposite for the negative value of the neutral-colour comfort variation, with coloured glazing more comfortable than the neutral one.

Statistical analyses were conducted for each question. Mixed-model analyses were first performed to investigate the main effects of coloured daylight and temperature, together with their interactions. The factor coloured daylight referred to the two types of differences, neutral-blue and neutral-orange. Gender was also included as a covariate of the model as it has been reported to affect thermal evaluations [19]. Participant codes were used as a random factor of the model. In the case of significant effects of interactions, additional investigations with mixed-model analyses were conducted at each temperature level to assess the differences between the neutral-blue and the neutral-orange comfort variations. In the following, results refer to the neutral-colour comfort variation for each of the four comfort evaluations.

For thermal comfort, results indicate that the variation was significantly affected by the interaction between daylight colour and temperature ($F(1,145) = 5.98$, $p = 0.016$). Due to the presence of the interaction term, further analyses at each temperature level were performed. As a result, coloured daylight was shown to be a significant factor at 26°C only ($F(1,23) = 14.23$, $p < 0.001$), as the difference between the neutral-blue and the neutral-orange variation was significant. In particular, orange was evaluated as more thermally comfortable than neutral, and blue less thermally comfortable than neutral. An opposite trend is visible at 19°C, but it cannot be considered significant from the statistical analysis (Figure 2a).

For colour comfort, the interaction term was slightly significant as well ($F(1,145) = 3.15$, $p = 0.080$). Further analyses, performed at each temperature level, indicated that coloured daylight had a significant effect at 19°C only ($F(1,23) = 5.7$, $p = 0.024$), with a larger difference between the blue and the neutral glazing compared to that between the orange and the neutral glazing (Figure 2c). This result indicates that at the lowest thermal condition investigated, the neutral-colour comfort variation between blue and neutral is larger than that between orange and neutral. As a result, in a cold thermal condition, the blue light is evaluated as being less visually comfortable. Differences between blue and orange glazing in comparison with the neutral one were not significant anymore at the other temperature levels.

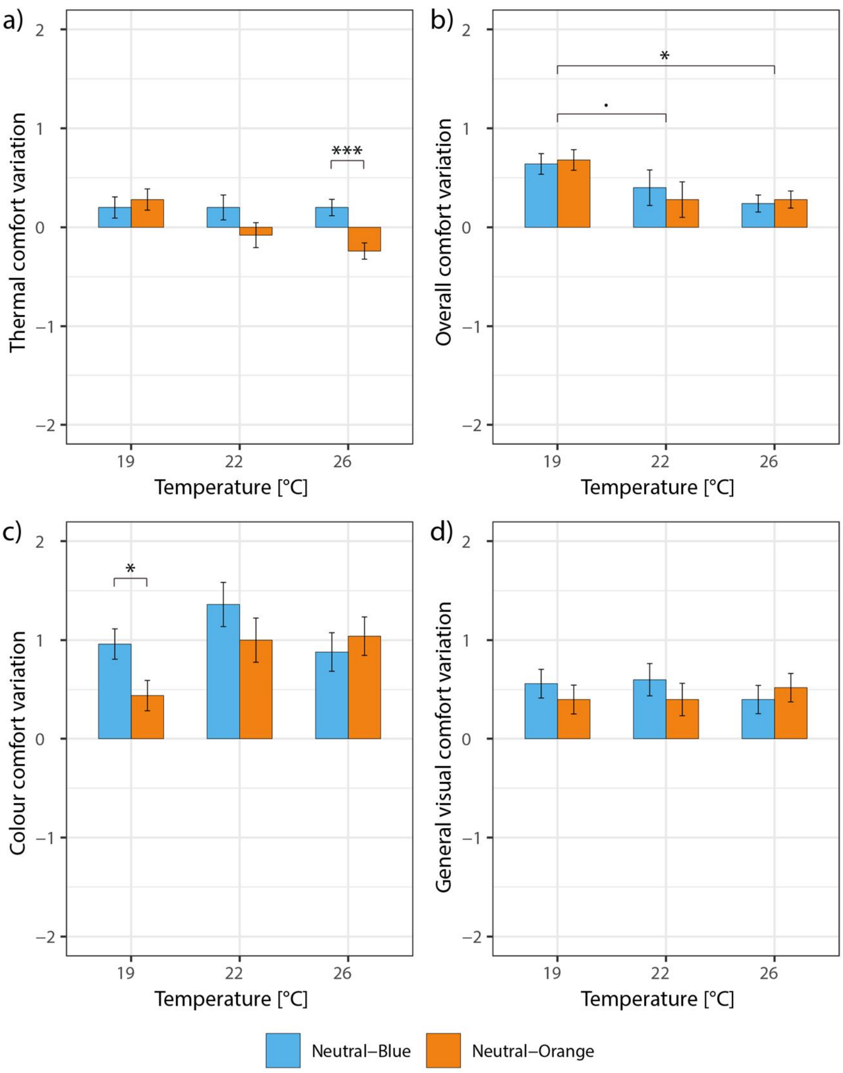

Figure 2: Neutral-colour comfort variation between the exposure to neutral and blue glazing and between neutral and orange glazing, at the three temperature levels. Graphs refer to: a) Thermal comfort, b) Overall comfort, c) Colour comfort; and d) General visual comfort. Significant effect of colour and temperature indicated with "." $p < 0.01$, "" $p < 0.05$, "**" $p < 0.01$, "***" $p < 0.001$.*

In terms of overall comfort, only temperature had a slightly significant effect ($F(1,145) = 3.90$, $p = 0.052$). Post-hoc pairwise comparisons performed with the Dunn Kruskal-Wallis multiple comparison test with p-values adjusted with the Benjamin-Hochberg method indicate that results under 19 °C were significantly different from those under 26°C ($p = 0.042$). Only a slightly significant difference was present between results at 19°C and those at 22°C ($p = 0.053$). Results indicate that, only at 19 °C, the overall comfort under both coloured glazing types was lower compared to that under the neutral glazing. The difference decreases with increasing temperature levels (Figure 2b).

For the general visual comfort, results were not affected by coloured daylight or by temperature, nor by their interaction. Gender was never a significant factor in any of the comfort evaluations.

The presented results suggest that cross-modal effects occur between daylight colour and temperature and that these effects are symmetrical. In particular, participants exposed to different coloured daylight changed their opinion regarding their thermal comfort (especially at higher temperatures, considered as comfortable [17]), resulting in a cross-modal effect of daylight on thermal perception. At the same time, comfort in relation to the colour of light was affected by the thermal environment, resulting in a cross-modal effect of temperature on visual perception. General visual comfort, however, did not change across temperature levels or glazing colour types: it is likely that participants were evaluating other visual aspects than colour, such as the quantity of light in the room or the view to the outside (factors that were similar throughout each experimental session).

Comfort votes variation between blue and orange glazing

Complementary to the previous analysis, this section still analyses comfort vote variations, but this time between the blue and the orange conditions only. Results are discussed in terms of "blue-orange comfort variation" (Equation 1), calculated for each participant.

$$\boldsymbol{blue - orange\ comfort\ variation = comfort_{blue} - comfort_{orange}} \quad (1)$$

Also in this case, considering that comfort votes range from 1 (very uncomfortable) to 5 (very comfortable), the maximum possible difference between the two votes is 4. A comfort vote variation equal to 0 indicates that participants did not change their comfort vote under the two colours. Positive values imply that participants rated the comfort under the blue condition more positively than under the orange, whereas negative values indicate a more comfortable condition evaluated under orange compared to blue. Results are not analysed statistically as in the previous section; instead, the frequency distributions of the variations are reported. This type of analyses is chosen as it gives more insights compared to the analysis of means, and it can be considered complementary to the results previously discussed. Figures 3 to 5 illustrate the distribution of blue-orange comfort variations for thermal, colour and overall comfort, at three temperature levels. Results on the general visual environment are discarded in this section due to non-significant results previously described.

Figure 3 illustrates that thermal comfort of participants was affected by coloured daylight, as pointed out in the previous section, as it changed between the blue and the orange conditions. In particular, thermal comfort was evaluated higher under the orange condition compared to the blue one by 40% of participants when exposed to 26°C (considered "neutral" in the corresponding thermal sensation scale) and by 44% of participants at 22°C (considered in between "slightly cool" and "neutral"). This percentage decreases at 19°C (considered in between "cool" and "slightly cool"). At this temperature, the percentage of people indicating a higher thermal comfort under orange in comparison with blue, equals that of people indicating an higher thermal comfort under blue in comparison with orange. Results confirm the cross-modal effect of coloured daylight on thermal comfort, with the orange glazing resulting in a more comfortable thermal condition than the blue one, especially under comfortable temperatures (26°C).

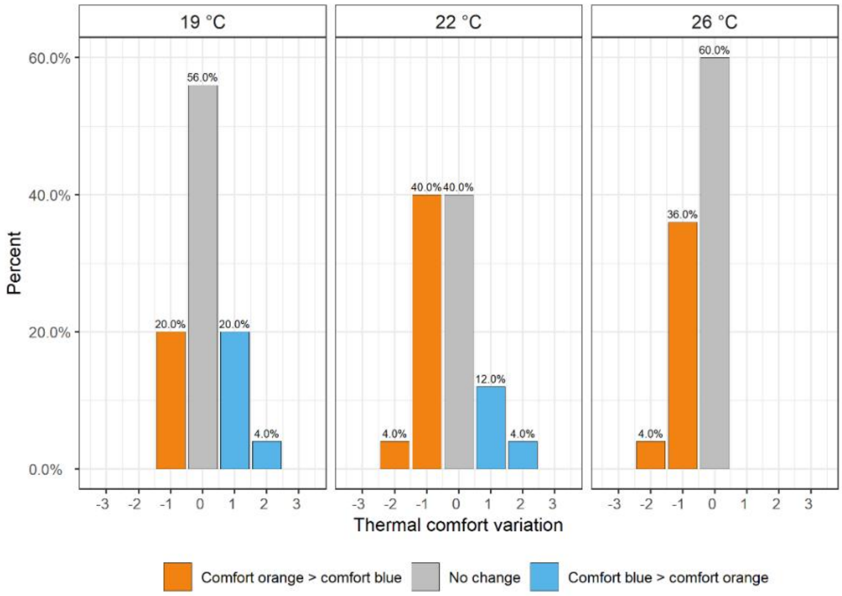

Figure 3: Thermal comfort vote variation between votes of participants exposed to blue daylight and the votes of participants exposed to orange daylight, at three temperature levels.

For colour comfort, we found – as expected – that votes were affected by coloured daylight. What is interesting to point out, by looking at Figure 4, is that results are influenced by the thermal environment. Orange is considered a more comfortable colour compared to blue at 19°C (by 44% of participants) and at 22°C (by 52% of participants), whereas the percentage of people considering blue a more comfortable colour than orange increases with temperature, with 44% at 26 °C compared with 12% at 19°C. Also, results here confirm the cross-modal effect of temperature on visual comfort, in terms of colour comfort.

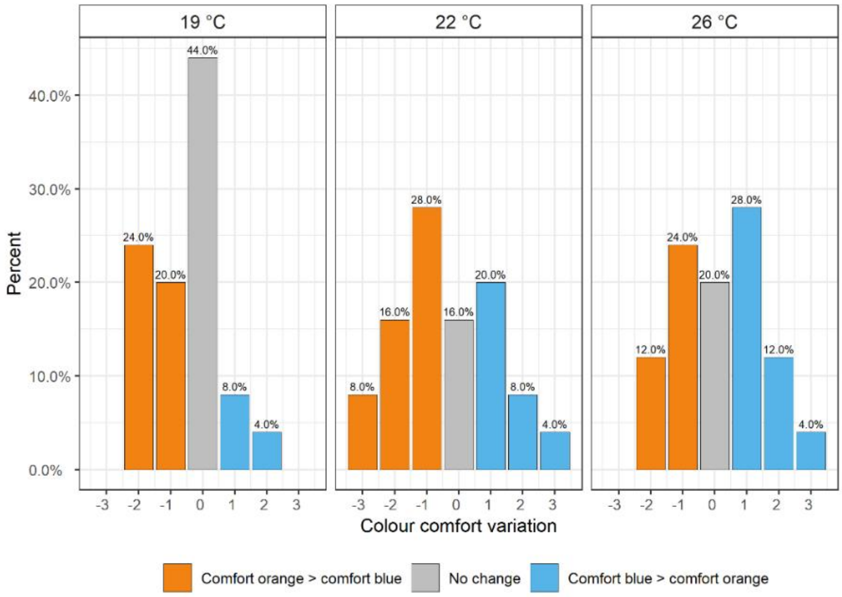

Figure 4: Colour comfort vote variation between votes of participants exposed to blue daylight and votes of participants exposed to orange daylight, at three temperature levels.

The overall comfort is affected by coloured daylight (Figure 5), as it changes from blue to orange. However, it does not show changes of votes that would have indicated a higher overall comfort under a particular colour (the negative and the positive differences are always similar), nor are these results affected by thermal conditions. On the other hand, the variation of votes between the two colours is larger at 22°C, whereas it is smaller at 19°C and at 26°C, in which most participants did not change the overall comfort vote at different colour exposure (variation equals 0).

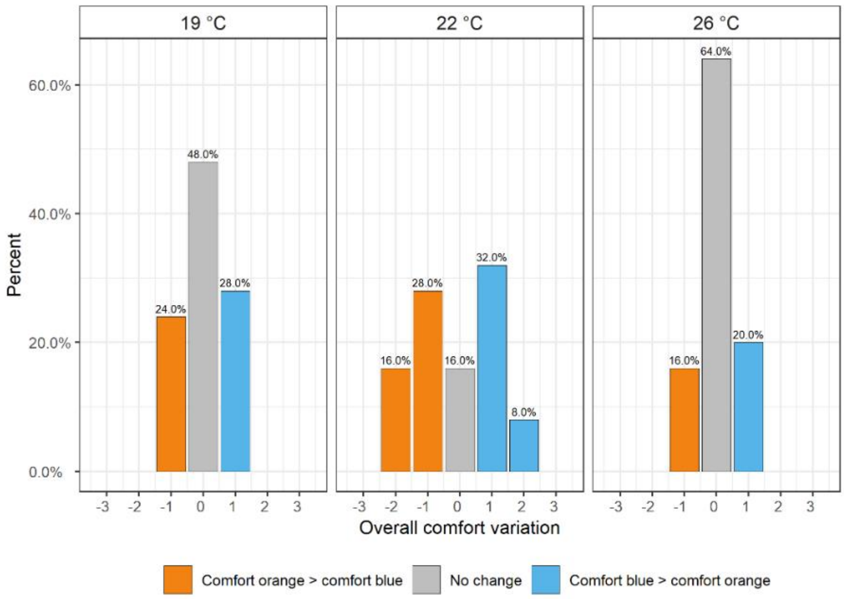

Figure 5: Overall comfort vote variation between overall comfort votes of participants exposed to blue daylight and the overall comfort votes of participants exposed to orange daylight.

Thermal, visual and overall comfort correlation

Figure 6 illustrates the correlation matrix with a Spearman correlation between the three investigated comfort votes: overall, visual (general and colour) and thermal.

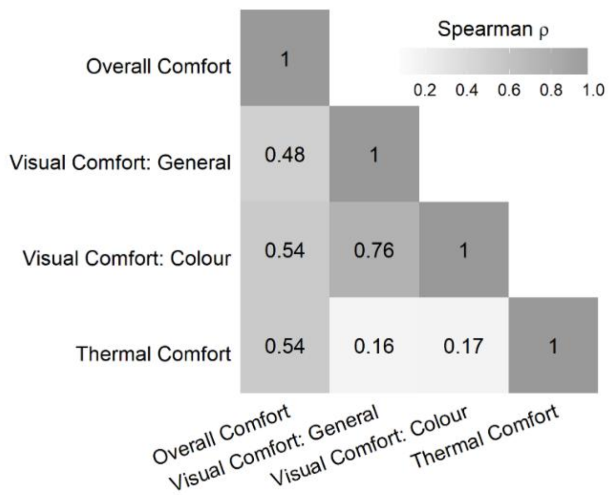

Figure 6: Correlation matrix between overall, visual (general and colour) and thermal comfort.

This time, all the votes at all temperature levels for the three glazing (neutral, blue and orange) are included in the analysis, which is not based on differences as were the two previous ones. It is possible to see that the overall comfort positively correlates with both thermal and colour comfort in a comparable way, a result that seems in contrast with previous studies, where overall comfort was mainly related to thermal comfort [20-22]. A possible explanation for the contrasting results is the nature of the present experiment, in which both thermal and visual parameters were the only factors varied across participants, resulting in the two principal factors strongly correlated with the overall evaluation. Figure 6 also shows that thermal and visual comfort do not correlate and that only 76% of the variation in colour explains the variation in the general visual environment, highlighting that colour, despite being a strong attribute of the visual environment, was considered by participants along with other factors in the general visual comfort evaluation.

Conclusions

This paper analyses thermal, visual and overall comfort of occupants exposed to combination of coloured glazing (orange, blue and a reference neutral) and indoor temperatures. The first part of the analysis focuses on the variations in comfort votes and is divided into two parts: in the first, the differences between comfort votes under one of the two colours (orange or blue) and those under the reference neutral glazing are analysed in terms of means and mixed model statistical analyses; in the second part, only differences between blue and orange glazing are considered and results are discussed in terms of distributions of comfort vote variations. Correlations across comfort votes are considered in the final part of the analysis.

From both analyses of comfort variation, we were able to confirm that symmetrical cross-modal effects occur between daylight colour and temperature. Cross-modal effects of coloured daylight on thermal comfort were observed, and orange glazing led to a more comfortable thermal environment than neutral and blue glazing especially at 26°C. Similarly, cross-modal effects of temperature on visual perception (colour comfort) were also observed as the blue light was evaluated as less comfortable than orange only in the cold thermal condition (19°C). Moreover, preferences with blue daylight over orange daylight increased with temperature (from 12% at 19°C to 44% at 26°C).

Despite the fact that changes in colour led to changes in overall comfort, neither blue nor orange resulted in more comfortable overall conditions. However, overall comfort variations were affected by temperature. More specifically, the difference between the overall comfort votes under both coloured glazing types and the reference glazing were larger at 19°C. Such differences decreased with increasing temperatures. This result indicates that the overall comfort perception under glazing with a colour tint might be lower than under a neutral glazing if the temperature is outside of the comfort zone. In comfortable thermal environments, this difference in overall comfort between coloured and neutral glazing may be smaller.

Finally, it was observed that overall comfort positively correlated to both visual and thermal comfort in a comparable way, due to the experimental design and the fact that colour was a strong attribute of the indoor environment. Evaluations of the general visual environment by the participants probably referred to other visual factors than the colour, as indicated by the correlation results and by the fact that results were not affected by coloured daylight.

Findings suggest that, in the presence of glazing with a colour tint such as for “smart” window technologies, thermal comfort should be investigated together with the most commonly studied visual comfort. Moreover, thermal conditions should also be considered in parallel with the visual ones as their combination might affect visual and overall comfort of buildings’ occupants.

References

1. Birren F (1984), *Color & Human Response: Aspects of Light and Color Bearing on the Reactions of Living Things and the Welfare of Human Beings* (First Edition), New York, NY: Wiley.
2. Shamsul BMT, Sia CC, Ng Y and Karmegan K (2013), Effects of light's colour temperatures on visual comfort level, task performances, and alertness among students, *American Journal of Public Health Research*, **1**, 159-165.
3. te Kulve M, Schellen L, Schlangen LJM and van Marken Lichtenbelt WD (2015), The influence of light on thermal responses, *Acta Physiologica*, **216**, 163-185.
4. Huebner GM, Shipworth DT, Gauthier S, Witzel C, Raynham P and Chan W (2016), Saving energy with light? Experimental studies assessing the impact of colour temperature on thermal comfort, *Energy Research and Social Science*, **15**, 45-57.
5. Fanger PO, Breum NO and Jerking E (1977), Can colour and noise influence man's thermal comfort? *Ergonomics*, **20**, 11-18.
6. Bennett CA and Rey P (1972), What's so hot about red?, *Human Factors: The Journal of the Human Factors and Ergonomics Society*, **14**, 149-154.
7. Judd DB, MacAdam DL, Wyszecki G, Budde HW, Condit HR, Henderson ST and Simonds JL (1964), Spectral distribution of typical daylight as a function of correlated color temperature, *Journal of the Optical Society of America*, **54** (8), 1031-1040.
8. Lee RL and Hernández-Andrés J (2005), Colors of the daytime overcast sky, *Applied Optics*, **44** (27), 5712-5722.
9. Aste N, Leonforte F and Piccolo A (2018), Color rendering performance of smart glazings for building applications, *Solar Energy*, **176**, 51-61.
10. Aste N, Buzzetti M, Del Pero C, Fusco R, Testa D and Leonforte F (2017), Visual performance of yellow, orange and red LSCs integrated in a smart window, *Energy Procedia*, **105**, 967-972.
11. Arbab S, Matusiak BS and Klöckner CA (2018), Colour shift of interior surfaces with advanced glazings, *Journal of the International Colour Association*, **21**, 10-35.
12. Liang R, Kent M, Wilson R and Wu Y (2019), Development of experimental methods for quantifying the human response to chromatic glazing, *Building and Environment*, **147**, 199-210.
13. Arbab S, Matusiak BS, Martinsen FA and Hauback B (2017), The impact of advanced glazing on colour perception, *Journal of the International Colour Association*, **17**, 50-68.
14. Zinzi M (2006), Office worker preferences of electrochromic windows: a pilot study, *Building and Environment*, **41**, 1262-1273.
15. Chinazzo G (2019), Daylight and temperature in buildings: interaction effects on human responses, *PhD Thesis*, Ecole polytechnique fédérale de Lausanne (Switzerland).
16. Chinazzo G, Wienold J and Andersen M (2019), Effect of indoor temperature and coloured glazing on visual perception of daylight, *Private Report*.
17. Chinazzo G, Wienold J and Andersen M (2018), Combined effects of daylight transmitted through coloured glazing and indoor temperature on thermal responses and overall comfort, *Building and Environment*, **144**, 583-597.
18. Keeling TP, Roesch EB and Clements-Croome D (2016), Cognitive appraisals affect both embodiment of thermal sensation and its mapping to thermal evaluation, *Frontiers in Psychology*, **7** (800), 1-12.
19. Karjalainen S (2012), Thermal comfort and gender: a literature review, *Indoor Air*, **22** (2), 96-109.
20. Buratti C, Belloni E, Merli F and Ricciardi P (2018), A new index combining thermal, acoustic, and visual comfort of moderate environments in temperate climates, *Building and Environment*, **139**, 27-37.
21. Frontczak M and Wargocki P (2011), Literature survey on how different factors influence human comfort in indoor environments, *Building and Environment*, **46**, 922-937.
22. Kim J and de Dear R (2012), Nonlinear relationships between individual IEQ factors and overall workspace satisfaction, *Building and Environment*, **49**, 33-40.