The effect of short exposure to coloured light on thermal perception: a study using Virtual Reality

Giorgia Chinazzo
École Polytechnique Fédérale de Lausanne

Kynthia Chamilothori
École Polytechnique Fédérale de Lausanne

Jan Wienold
École Polytechnique Fédérale de Lausanne

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G. Chinazzo, K. Chamilothori, J. Wienold, and M. Andersen
Laboratory of Integrated Performance in Design (LIPID)
Ecole polytechnique fédérale de Lausanne (EPFL)
Lausanne, Switzerland
{giorgia.chinazzo, kynthia.chamilothori, jan.wienold, marilyne.andersen}@epfl.ch

***Abstract*— This study investigates the effect of short exposure to coloured light on thermal perception. To give the impression of natural daylight passing through coloured filters, but avoiding the drawbacks of conducting an experiment with daylight, continuously changing due to daily and seasonal variations, and to weather conditions, we investigate the use of Virtual Reality as a means to control the visual conditions, creating a hybrid environment with thermal and visual stimuli from the real and virtual world, respectively. Two temperature levels (24 °C and 29 °C) are controlled in a climate chamber, while three visual conditions (orange, blue and neutral colour filters) are displayed in the Virtual Reality headset. Results of a between-subjects experiment show that the coloured light led to different thermal evaluations. In particular, under orange light conditions at 24 °C, subjects felt warmer, less comfortable and judged the thermal environment as less acceptable than under the other colours at the same temperature.**

***Index Terms*— daylight, hue-heat-hypothesis, temperature-colour interaction, virtual reality.**

I. Introduction

The evaluation of indoor comfort requires a thorough understanding of how people perceive and respond to the indoor environmental factors, namely air quality, acoustic ambience, visual and thermal conditions. In the last decades studies have focused on the effects of their interactions on comfort perception [1]–[9], given that the human sensory system is not modular but integrates and responds to different environmental factors occurring simultaneously [10]. The hue-heat-hypothesis, in particular, focuses on the influence of visual parameters on thermal perception, asserting that colour toward the red end of the spectrum are perceived warmer than colour toward the blue end of the spectrum [11]. Positive outcomes from experiments investigating this hypothesis can lead to application in building design and operation for energy saving purposes [9]. To this aim, it is necessary to conduct further experiments to investigate conditions that are similar to real world settings. A recent literature review on the topic by the authors highlighted the necessity to investigate the effect of coloured daylight on thermal perception [12]. Experiments that use daylight as one of their independent variables face the challenge of a variable that is difficult to control due to daily and seasonal variations, and change in weather conditions [13]. To address this problem, we investigate the use of virtual reality as a means to control the visual conditions independently of the external ones, creating a hybrid environment with stimuli from both the real and virtual world. The immersion and interaction of people with a virtual environment have been shown to be factors of importance [14]-[15], suggesting the use of immersive virtual reality as an empirical research tool. The virtual reality environment developed and used in this study has been recently tested by the authors as an independent visual stimulus and shown to be an adequate surrogate for real environments in daylight perception studies [16]. Similarly, benchmarking studies on user performance in virtual reality show similar user behavior in the real and virtual environment [17].

II. Hypothesis

We hypothesize that short exposure to coloured light in immersive virtual reality will affect people's thermal perception. In particular, our hypothesis asserts that people experiencing an orange light condition would feel warmer and less comfortable than people experiencing a "neutral" or blue light condition.

III. Methodology

The methodology followed in this study consists of the combination of stimuli in the real and virtual environment, with the aim to investigate the effect of coloured daylight conditions on thermal perception. In order to increase the realism of the virtual scenes, we decided to use projected photographs rather than simulation. These images were taken in the test room where the experiment took place, with three different coloured filters applied on the glazing of the north façade. Using 180° HDR photographs, these conditions were then reproduced into immersive virtual reality scenes. Through this procedure, all participants saw one of three visual stimuli projected in the virtual reality headset, corresponding to the neutral, orange and blue coloured condition. By combining the participants' visual immersion in the virtual reality projection and bodily immersion in the thermal conditions of the climate chamber, we can ensure their exposure to controlled colour and temperature stimuli.

A. Experimental Design

A completely randomized full factorial design was selected, for a total of 6 combinations, testing two levels of temperature (24 °C and 29 °C), and three levels of colour (neutral, blue and orange) displayed in the immersive virtual reality. As the experiment was conducted in the summer, the two temperature ranges correspond to commonly found conditions in non-air-conditioned office-rooms in mid-Europe, and to thermal conditions considered as being outside of the comfort range based on the SIA [18] norm. As a between-subjects design was used, each participant experiences just one combination of temperature and colour. The sample size for each colour condition was 21 subjects, distributed in the temperature groups as shown in Table 1 below. The measurements of operative temperature during the experimental sessions show that the average value fell within a range of ± 0.5 °C among the three colour exposures at both 24 °C and 29 °C temperature levels (Table 2). Relative humidity was kept between 45-55% and air velocity below the threshold of 0.1 m/s. Temperature-colour combinations were counterbalanced to ensure that testing occurred equally often in the morning and afternoon.

TABLE I. SAMPLE SIZE PER COLOUR-TEMPERATURE COMBINATION

	24 °C level [-]	29 °C level [-]
Blue	12	9
Neutral	12	9
Orange	12	9

TABLE II. MEAN MEASURED OPERATIVE TEMPERATURE

	24 °C level [-]	29 °C level [-]
Blue	23.6	29.2
Neutral	24.0	29.3
Orange	23.8	29.1

The thermal perception of the participants was recorded through their responses to a verbal questionnaire while they were experiencing the immersive virtual scene. The verbal questionnaire was supported by a visual reference of each item scale in the virtual reality environment. The dependent variables are divided into two main categories: (i) subjective thermal perception and (ii) objective thermal perception. Four questions fall into the first category (i.e., thermal sensation, comfort, preference and judgement) and one into the last one (i.e., temperature estimation). For a summary of the dependent and independent variables used in the study see Table 3.

TABLE III. OVERVIEW: INDEPENDENT AND DEPENDENT VARIABLES

Independent Variables	
Temperature	Low temperature range (24°C) or high temperature range (28°C)
Colour	Neutral, blue, or orange
Dependent Variables	
Thermal Sensation	At this precise moment, how are you feeling? Scale (1:7): Cold - Cool – Slightly cool – Neither cool nor warm - Slightly warm - Warm - Hot
Thermal Comfort	Do you find this condition: Scale (1:5): Very comfortable – Comfortable – Slightly Uncomfortable – Uncomfortable – Very Uncomfortable
Thermal Preference	How would you prefer to feel now? Scale (1:7): Much cooler – Cooler – Slightly cooler – No change – Slightly warmer – Warmer – Much Warmer
Thermal Judgement	How do judge the thermal environment on a scale from 0 to 100, where 0 is unacceptable and 100 is acceptable? Scale (1:100): Unacceptable - Acceptable
Temperature Estimation	Could you please estimate the room temperature in °C?

B. Participants

Participants were contacted via email with a pre-selection questionnaire, used to select the candidates that fulfilled eligibility criteria regarding normal BMI, age under 35, and no color vision deficiency. Once selected, subjects could choose a timeslot for their experimental session. The sessions were set to allow the balancing between genders, timing of the session (morning or afternoon), temperature condition, and colour exposure. Of the sixty-three participants tested, thirty-one were men and thirty-two were women. Gender balance was respected across temperatures with eighteen men and women in the 24 °C level and thirteen men and fourteen women in the 29 °C level. Following a single-blind procedure, subjects were told they were participating in a study investigating the effect of different scenes displayed in the immersive virtual reality on physiological responses. Physiological responses were also recorded, but their analysis is not reported in this paper. Subjects were told that their responses to the verbal questionnaire would be compared with their physiological measurements. To this end, they were asked to give evaluations that reflected their perception in the exact moment when the questions were asked.

C. Experimental Set-up and Equipment

1) Visual stimuli in the virtual environment

To generate the virtual scenes, the experimental room was set up to create four different visual conditions that were recorded and reproduced in the virtual reality: one with artificial light and curtains closed, and three with daylight passing through the coloured filters, corresponding to neutral, blue, and orange colour, illustrated in Fig. 1. The scenes were photographed using a 180° fisheye lens from the viewpoint of a participant seated in the middle of the room, resulting to High Dynamic Range (HDR) image per condition, each calibrated using two luminance reference measurements in the corresponding real environment. The HDR images were tone mapped using the local adaptation of the Reinhard02 photographic tone mapping algorithm [19], transformed into BMP files using *ra_bmp* with a gamma correction of 2.0, and applied as cubemap projection with the procedure developed in [16] to create 180° immersive scenes that can be projected onto Oculus Rift CV1. In the resulting virtual reality environment, the user of the headset can freely explore the space by moving their head and looking around. Although the user was immersed in a 360° visual environment, half of the scene was black and half of the scene was visible, corresponding to the 180° fisheye photograph of the real environment (Fig. 1, d). The equipment for the visual stimuli consisted of the Oculus Rift CV1 virtual reality headset, with field of view of 110° and resolution of 1080×1200 pixels per eye. The maximum luminance of the display, measured at the lens, was 80 cd/m2, due to current technical limitations.

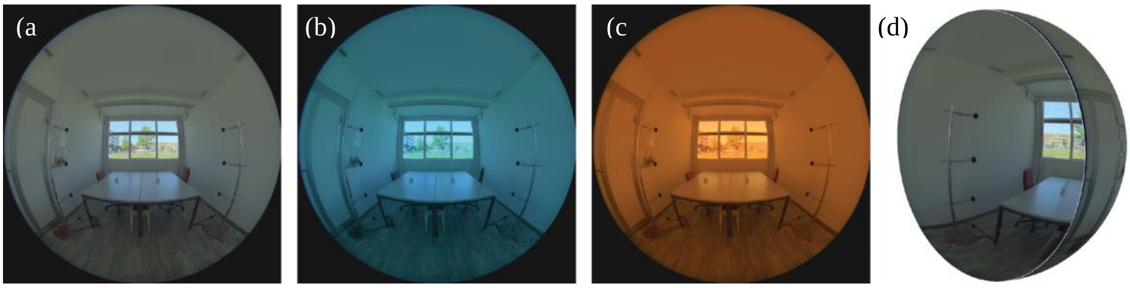

Figure 1. Tone mapped fisheye photographs of the neutral (a), blue (b) and orange (c) colour conditions, and illustration of the 180° scene (d).

2) Thermal Stimuli in the real environment

The experiments were conducted in the “DEMONA” test room, a climate chamber facility on the EPFL campus. The test room is designed to control and keep within ranges the principal indoor environmental factors responsible for thermal comfort: temperature, humidity and air velocity. In order to keep the visual conditions constant for all participants before their wearing the virtual reality headset, only artificial light was used, and daylight was prevented to enter the test room with white solar blackout curtains positioned on the north and south facing windows. The room was equipped with sensors that measure with a sampling period of one minute the air and globe temperature, the relative humidity, the CO_2 content, and the air velocity. Temperature measurements were recorded on both the left and right side of the participant seated in the middle of the room (Fig. 7).

D. Experimental Protocol

Each experimental session lasted approximately 30 minutes and followed the same protocol, shown in Table 4. All participants were asked to conform to a similar clothing level. Once inside the test room, the participant received a short explanation of the study and was asked to read an information sheet and sign a consent form. After this step, they filled a questionnaire on their background information. The participant was then shown how to wear the VR headset and adjust its fit in a training scene, and was instructed to limit their head movements within the boundaries of the visible 180° scene. For the remainder of the session, the participant was immersed in the virtual reality environment. The first scene they were exposed to is the test room with artificial light and closed curtains, followed by the scene of the coloured environment, where only one colour condition was shown to each participant. Few additional questions not related to thermal perception were asked to allow for colour adaptation. The participant was exposed to the temperature in the test room for an average of 20 minutes before the thermal perception questionnaire.

TABLE IV. STAGES IN THE EXPERIMENTAL PROTOCOL

1. Introduction	*2. Consent*	*3. Questionnaire*	*4. VR Scene*	*5. VR Scene*	*6. VR Scene*	*7. Questionnaire*
Short Explanation	Information Sheet and Consent Form	Background information	Training scene	Control scene (curtains)	Colored light scene (neutral, blue, orange)	Thermal perception

IV. RESULTS

In the following sub-sections we analyse the effects of colour on the subjective and objective evaluation of thermal perception. The analysis consists of box-plots and statistical results referring to a two-way between subjects Analysis of Variance (ANOVA) are reported to evaluate the main effects of colour and temperature and their interaction on the different thermal perception evaluations, for a significance level α of 0.05. Post-hoc $Tuckey_a$ (Honestly Significant Difference) tests are conducted for each thermal evaluation to carry out all possible pairwise comparisons across the three levels of the factor “colour” (neutral, blue and orange), using a significance level α of 0.05.

A. Effect of colour on subjective thermal perception

Figures 2-5 show the subjective responses related to the thermal sensation, thermal comfort, thermal preference and thermal judgement, respectively. The left hand side of each figure indicates the results for the 24 °C level, while the right hand side for the 29 °C level. Within each temperature level, the single boxes illustrate the thermal responses for each colour. The figures demonstrate that the short exposure to coloured light in the immersive virtual reality led to different thermal perception evaluations. The fact that we observe different responses confirms that the immersive virtual reality can be used to evaluate thermal-visual interactions, even with a short exposure time. The results of a two-way ANOVA on the effects of colour and temperature exposure on thermal perception show that the main effect of colour is significant on the evaluations of thermal sensation (F = 4.7, p = 0.012), thermal comfort (F = 5.9, p = 0.004), and thermal judgement (F = 6.1, p = 0.003). Thermal preference demonstrates a less strong result (F = 3.2, p = 0.047), which can still be considered significant for a significance level α of 0.05. The main effect of temperature is always significant (with p < 0.01), while the interactions between colour and temperature are significant only for the thermal comfort evaluation (F = 3.9, p = 0.025). This can be explained by the fact that the blue light is considered comfortable at 24 °C, in line with the evaluation of the neutral condition, and slightly uncomfortable under 29 °C, in line with the evaluation of the orange colour condition, as can be seen in Fig. 4. The post-hoc Tuckey$_a$ (HSD) tests showed that with α = 0.05, there was a statistically significant difference only between the means of the evaluations in orange and neutral light conditions (p = 0.012 for thermal sensation, p = 0.003 for thermal comfort, and p = 0.002 for thermal judgement). Figure 2 shows a greater effect of colour within the 24 °C level, considered slightly warm by the majority of the people. In this thermal level, people exposed to the orange condition felt warmer and less comfortable, and considered the thermal environment less acceptable than under the neutral and blue conditions.

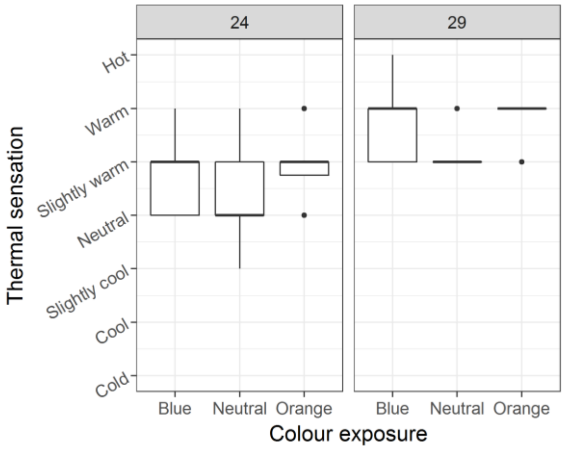

Figure 2. Thermal sensation evaluation of subjects exposed to the three colours for the two temperature levels (24 °C, left, 29 °C, right).

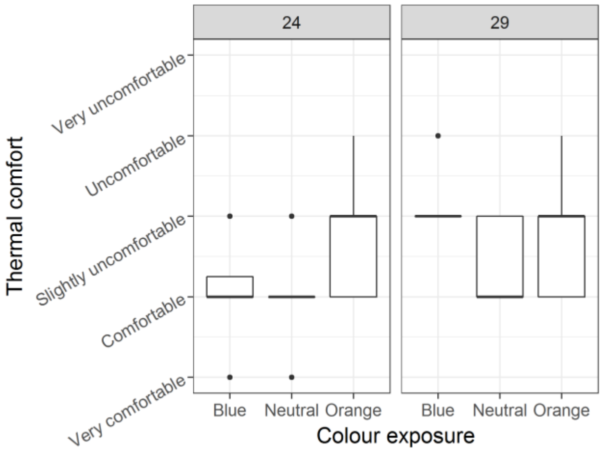

Figure 3. Thermal comfort evaluation of subjects exposed to the three colours for the two temperature levels (24 °C, left, 29 °C, right).

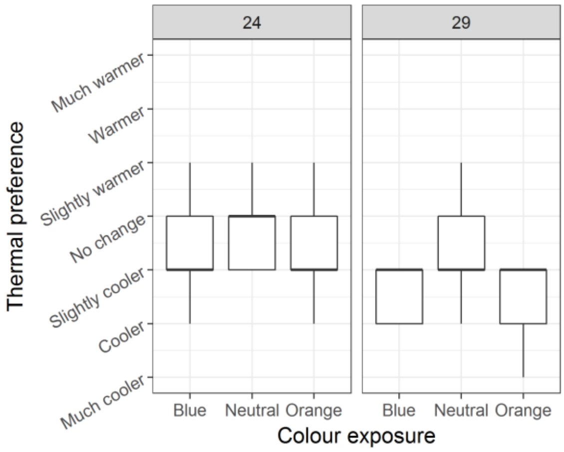

Figure 4. Thermal preference evaluation of subjects exposed to the three colours for the two temperature levels (24 °C, left, 29 °C, right).

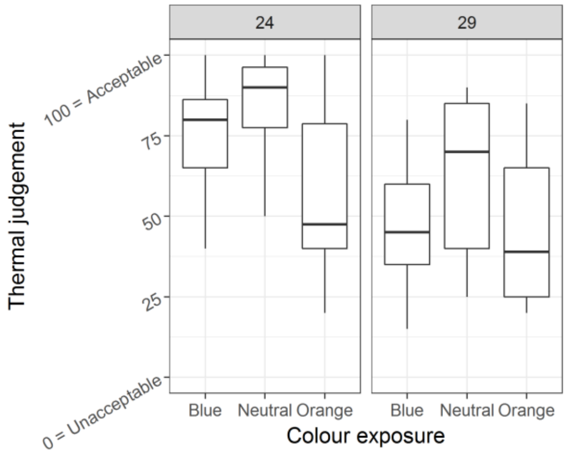

Figure 5. Thermal judgement evaluation of subjects exposed to the three colours for the two temperature levels (24 °C, left, 29 °C, right).

B. Effect of colour on objective thermal perception (temperature estimation)

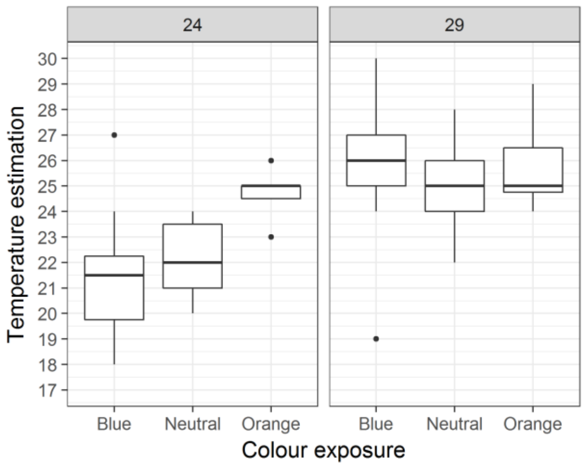

Figure 6. Temperature estimation of subjects exposed to the three colours for the two temperature levels (24 °C, left, 29 °C, right).

Figure 7. Photograph of a participant using the virtual reality headset and experiencing an immersive scene in the test room.

The same conclusions can be drawn for the objective thermal perception, where subjects were asked to estimate the room temperature. A two-way ANOVA revealed that the main effect of colour is significant ($F = 4.4$, $p = 0.016$) as well as the main effect of temperature ($F = 18.09$, $p = 0.000$), while there are not significant interactions ($F = 0.58$, $p = 0.56$). A post-hoc Tuckey$_a$ test shows statistically significant difference for $\alpha = 0.05$ only between the means of the evaluations in the orange and neutral light conditions ($p = 0.014$). The effect of exposure to orange light is much clearer in the 24 °C level (Fig. 6), where temperature under orange exposure is estimated as 3 and 4 °C higher than in the other two colour conditions. Under 29 °C, temperature estimation is similar across colour conditions.

V. Conclusion

We found that short exposure to light displayed in virtual reality led to different evaluations of thermal perception, showing that this immersive technology can be used to test visual and thermal interactions. Most significant differences can be found between neutral and orange light exposures. We can conclude that under slightly uncomfortable thermal conditions (slightly warm in this case, as the experiment was conducted in the summer), a short exposure to coloured light can affect thermal evaluations of people even under the same thermal conditions. People feel warmer, more uncomfortable and consider the thermal environment less acceptable when exposed to orange light compared to blue or neutral light conditions. Similarly, when investigating objective thermal perception through temperature estimation, exposure to orange light led to higher estimated temperature compared to the other two visual conditions. However, the post-hoc Tuckey test revealed no significant differences between the blue light and the other two conditions for any of the studied evaluations of thermal perception. The experimental design, testing two levels of temperature, allowed the investigation of interactions between colour and thermal conditions. Findings show that the effect of colour on thermal perception is greater at 24 °C (still considered slightly warm), indicating that the effects of thermal stimuli at 29 °C predominate over the colour stimuli on the evaluation of thermal perception. Based on these findings and considering the between-subjects design of this study, we foresee a second series of experiments to increase the sample size and reduce the variability within subjects.

Although the use of virtual reality in this study greatly increased the control over the visual stimuli, one of the main challenges that emerge is the reproduction of colour on the headset display. The selection of tone-mapping operators can greatly affect the colour rendering of the scene, which can in turn directly impact the effect of exposure to colour. The limited luminance of the virtual reality display is another factor of importance, which should be investigated to test the reproducibility of the findings in real environments. Future studies are encouraged to compare subject thermal perception across combinations of thermal and visual conditions in real and virtual environments, and further our understanding of the capabilities and limitations of immersive virtual reality in experimental studies.

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