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Combined effects of daylight transmitted through coloured glazing and indoor temperature on thermal responses and overall comfort

G. Chinazzo*, J. Wienold, M. Andersen

Laboratory of Integrated Performance in Design (LIPID), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole polytechnique fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland

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ABSTRACT

This study investigates the effect of daylight transmitted through three coloured glazing types (blue, orange and neutral) on thermal responses and overall comfort, at three temperature levels (19 °C, 22 °C and 26 °C). The goal is threefold: (i) understand whether the colour can affect a perception other than the visual (i.e., the thermal); (ii) study whether colour interacts with temperature influencing thermal responses; (iii) examine the combined effect of colour and temperature on overall comfort. A total of 75 participants took part in a controlled experiment. Thermal responses were estimated with questionnaires about subjective thermal estimation and physiological measurements (skin temperature, heart rate and skin conductance). Statistical analyses revealed that daylight transmitted through coloured glazing affected participants' thermal responses, mainly psychologically rather than physiologically, resulting in a *colour-induced thermal estimation*. With a blue glazing, people felt colder and less comfortable than with a neutral one. With an orange glazing, people felt warmer and more comfortable than with a blue one. Results were independent of temperature levels, but occurred mainly at temperatures perceived as comfortable (26 °C) or close-to-comfortable (22 °C). Overall comfort was also affected, both at the beginning of the colour exposure by only the glazing's colour, and at the end of the exposure by both colour and temperature. Given the significance of effects for the short exposure time and for temperature ranges that are realistic indoors, these findings should be taken into consideration in practice for both comfort and energy savings purposes, especially in transitional spaces.

1. Introduction

Windows' role in architecture is fundamental to achieve design features required or desired in a building. Windows' shape, dimension, location on a façade and glazing type can be used to this end, resulting in changes in quality and quantity of the transmitted daylight. The majority of studies investigating the impact of windows on daylight appearance, visual perception and visual comfort, mainly focused on shading controls, window size and glazing transmittance [1–5]. The tint of the glazing has also been investigated given the increasing use of solar-protective glazing against overheating, electrochromic glazing to prevent glare, coloured PV panels or more simply of coloured glazing for architectural and aesthetic purposes. Such technologies distort the spectrum of the transmitted daylight, affecting its quality, appearance and perception. These visual effects have been analysed in previous studies [6–10]. Nevertheless, to the authors best knowledge, no investigations exist on the implication of tinted glazing and the resulting transmitted and coloured light on perceptions other than the visual one.

According to the hue-heat-hypothesis [11], colours influence the thermal perception of people, with colours toward the red end of the spectrum resulting in warmer perception, and colours toward the blue end of the spectrum resulting in colder perception. The hue-heat-hypothesis thus relates – by definition - mainly to subjective thermal estimation rather than to physiological responses, two aspects of what we will refer to as “thermal responses”. Nevertheless, the effect of colours on physiological responses has also been investigated in previous studies. A literature review on the topic conducted by the authors, investigating the effect of different types of coloured stimuli on thermal responses (including both subjective thermal estimation and physiological responses), suggested that the colour of the light rather than the ones of objects, furniture or architectural components (walls, ceiling and floor) is more likely to result in a significant effect [12]. In addition to this, while there is a large number of studies about the effect of coloured artificial light sources on thermal responses, research about daylight transmitted through coloured glazing is still missing.

Moreover, no studies exist on the effect of the transmitted coloured

* Corresponding author.
E-mail address: giorgia.chinazzo@gmail.com (G. Chinazzo).

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daylight on overall comfort or on how colours interact with the indoor temperature affecting both thermal and overall responses.

To address the aforementioned research gaps, this paper describes an experimental study investigating for the first time the combined effect of daylight transmitted through coloured glazing (from now on referred to as "coloured daylight") and indoor temperature on thermal responses and overall comfort. The thermal responses of participants are estimated with a mixed method, meaning an approach that combines both qualitative and quantitative methods [13]. As a result, thermal responses are evaluated in terms of subjective thermal estimation by means of questions and in terms of physiological responses. The investigation was entirely carried out in a semi-controlled test room designed *ad-hoc* for the purpose of the study, where 75 participants were completely immersed under both visual and thermal factors. This experimental method was chosen against, for instance, a scale model approach like in Ref. [7] to allow the thermal and chromatic adaptation for the participants' full body. To the authors best knowledge, this is the only study where temperature-colour interactions have been investigated with the use of daylight as the only light source.

2. State of the art

Coloured daylight, besides affecting people's visual appraisal, can have an impact on types of perception usually related to other indoor factors (in our case, the thermal), resulting in *cross-modal main effects*. In addition to this, coloured daylight can interact with other indoor factors (in our case, the temperature), resulting in (i) *cross-modal interaction effects* when it influences the perception correspondent to the other indoor factors in a different way at various levels of the factor (in our case, at different temperature levels), or in (ii) *simple main and interaction effects* when affecting a third type of perception (in our case, the overall comfort). Fig. 1 summarises these concepts. The following sections review experimental studies dealing with the aforementioned effects of coloured light and temperature on thermal responses (both subjective thermal estimation and physiological response) and overall comfort. Considering the lack of studies on daylight, the following review will consider only investigations based on the use of electric lighting, either coloured or with different correlated colour temperature (CCT).

2.1. Cross-modal main effect of coloured light on thermal responses

The majority of the studies using electric lighting, either coloured or with different CCT, reveal an effect of colour on subjective thermal estimations of people [14–18]. The effect is in line with the hue-heat-hypothesis, showing that orange/red lighting leads to warmer perceptions and blue lighting to cold ones. Nevertheless, only one study reports a significant effect of coloured electric light on all the thermal subjective evaluations [18], while the others found an effect only for some of them. Differences can be explained by the various types of electric light, temperature exposure and experimental design used. In particular, we believe that the use of more saturated colours as the ones used by Albers at al. [18], rather than the use of different CCT, might lead to a larger agreement across the questionnaire results. This hypothesis is reinforced by results of Fanger et al. [19], where red coloured electric light led to slightly lower preferred temperature compared to blue. The criticism moved toward the use of coloured electric light instead of more natural and common CCT [20] would not apply to coloured daylight as this latter is a result of technologies already applied in buildings.

In the literature on colour and thermal responses, physiological measurements were recorded together with subjective thermal evaluations in very few studies so far [15,16,19]. They all reported no significant effect of coloured light or of light with high and low CCT on physiological responses, which were predominantly skin temperature and core body temperature. Body temperatures in response to coloured electric light have mainly been studied in relation to the non-visual effects of light, following the discovery of the new photoreceptor in the eye [21]. In particular, it has been found that exposure to blue electric light (wavelengths of 480 nm) or to light with high CCT at night or early in the morning lead to higher core body temperature [22,23]. No effect on skin temperature has been found, except for one study, where higher skin temperature of the feet was detected under a CCT of 3000 K [24]. On the other hand, studies that did not report the time of exposure found a significant effect of CCT on skin temperature, with lower temperature under yellowish electric light (CCT of 3000 K) [25], [26]. These two studies exposed their participants to dynamic thermal environment, with increasing or decreasing temperature. Also this time, the great variations in experimental design, thermal conditions and colour exposure, can explain the differences across results. In particular, as pointed out by other researchers [22], the combination of the time-of-the-day of the exposure and the thermal environment might be essential for the understanding of the effect of coloured lighting on body temperature, both skin temperature and core body temperature.

Other than skin temperature and core body temperature, other types of physiological responses were measured in past studies. A recent literature review on the effect of colour on non-image-forming aspects in humans reported conflicting results about the effect of coloured electric light on heart rates [27]. Nevertheless, results are difficult to compare due to the exposure time (usually very short, such as 1 min [28–31]) and/or the fact that coloured lights were usually projected on a white wall or were shown on a screen, rather than immerging the body of participants [32]. Skin conductance levels were also investigated in some of the aforementioned studies, and were never significantly affected by coloured electric light [28,31,33]. Nevertheless, skin conductance levels were affected by coloured light in other studies [34–36], indicating that additional investigations are needed on the topic.

2.2. Cross-modal interaction effect of coloured light and temperature on thermal responses

In the aforementioned investigations on coloured electric light, only one study analysed the effect of coloured electric light at various static temperature levels on subjective thermal estimations [18]. They concluded that the effect of coloured lighting is independent of

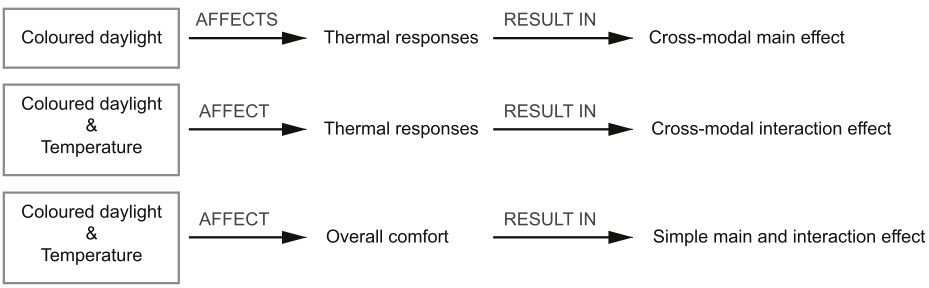

Fig. 1. Combined effect of coloured daylight and temperature on thermal responses and overall comfort.