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Saving energy with light? Experimental studies assessing the impact of colour temperature on thermal comfort

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ABSTRACT

We tested whether the colour temperature of the illumination (realised through manipulating the ceiling light) impacted on thermal comfort, based on the hypothesis that a lower colour temperature is associated with feeling warmer and a higher colour temperature with feeling cooler. If confirmed, then light might be a tool for energy-saving through allowing ambient air temperatures to vary over a wider range and hence reducing the need for space heating and cooling.

Testing took place in a climate chamber. In Study 1, comfort ratings were collected using thermal comfort surveys ($N = 32$). In Study 2, an observational design was used, where changes in clothing level, interpreted as thermal discomfort responses, were observed ($N = 32$). We compared comfort ratings and changes in clothing level under light with a colour temperature of 2700 K vs. 6500 K. Results partly confirmed the hypotheses: both self-report and observation indicated higher comfort under the low colour temperature. Further research will need to replicate findings in a real-world setting to see if light might indeed be a tool to modulate thermal comfort, and hence reduce usage of heating and cooling.

1. Introduction

Reducing energy consumption in residential and non-residential buildings is one of the main challenges faced in moving towards a more sustainable future. Over recent years there have been considerable bodies of research on areas such as retrofit strategies and 'smart technologies' (e.g. Refs. [20,19,73]). Extensive research has also been carried out on behaviour change programmes (for a review see Ref. [1]) such as giving occupants feedback on their consumption (e.g. [42,11]), and making energy 'visible' [28]. In this paper, we researched a different approach towards reducing energy consumption based on the idea of the 'hue-heat hypothesis' [3] which states that a warm (i.e. reddish/yellowish) ambient coloured light is felt as warm, while a 'cold' (i.e. bluish) coloured light is felt as (comparatively) cool. Whilst the main focus of this paper is to collect further evidence for the effect of light on thermal perception/comfort, the ultimate goal would be to use manipulation of the ambient light colour as a tool for energy-saving in buildings if temperatures could be lowered under a reddish/yellowish illumination in the heating season, or, conversely, be kept higher under bluish illumination in the cooling season.

As shown in a detailed analysis of papers published in major energy-related journals, there is comparatively little human-centred, social- science research in this field, as is truly multidisciplinary research [66]. Our work adds to this under-researched area by applying psychological theory to a practical energy-related problem using thorough experimental research.

1.1. The hue-heat-hypothesis

Starting point of the hue-heat-hypothesis is the idea of psychological distinction between "warm colours" and "cool colours". Blue, green and purple colours are considered to be cool, while yellowish and reddish hues are seen as warm [58]. In everyday life, the association between those colours and thermal temperature may be found for example, in the coding for taps, where red symbols refer to warm, blue symbols to cold water.

The distinction between warm and cool colours may be found since the 18th century [26], and was intensively elaborated in Goethe's colour theory [27]. This divide between warm and cool colours has also been found in colour naming patterns across fun-

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damentally different languages [48], and it has been shown that observers tend to associate certain colours with "warm" and others with "cool" [58]. Finally, the association between colour and temperature is also reflected in the association of colours with warm and cool objects, such as red with fire, and blue with ice [72].

In the following section, we review current evidence on the hue-heat-hypothesis.

We have only looked at those studies that have assessed thermal perception, not studies that look at what colours are characterized as 'warm' or 'cold'. Given the relative paucity of studies on the hue-heat-hypothesis, we reviewed all studies relating colour to thermal perception, not only those manipulating the colour of illumination, as tested in our studies.

When investigating the judgement of thermal temperature and colour of objects and material, effects opposite to the hue-heat-hypothesis have been found, according to which blue objects or materials are perceived to be warmer [32,53]. Ho et al. [32] suggested that it might be that we expect blue objects to feel colder; if they are then of the same temperature as a red object; we assume that in fact, the blue object must be warmer.

Another line of research investigated the effects of wall colours on the judgment of room temperature. Some of those studies have found effects in line with the hue-heat-hypothesis: Itten [41] and Clark [15] found that comfort was significantly impacted by wall colour, with participants feeling colder in blue/blue-green rooms. However, others did not observe any reliable effect of colour of the environment on the judgement of room temperature or comfort. Two studies exposed participants to differently coloured walls [30] or entire rooms decorated in different hues [61] and participants had to estimate the temperature in the different settings. Their temperature estimates did not differ significantly between settings. It might be that the substantially different outcome variable of temperature estimates as opposed to comfort ratings underlies the different findings, indicating that people may be able to dissociate between comfort feeling and temperature estimates. This idea is supported by the notion that self-reported thermal sensation, thermal preference, and thermal comfort are qualitatively different entities [7]. Finally, Houghton et al. [33] made participants watch coloured screens illuminated by red, green, and white light (spectral composition not given) and found no effect on self-reported thermal comfort; however, luminance varied significantly across the three settings which might have confounded results.

Most important to the present investigations, are those studies that evaluated the effect of illumination colour on the sensation or judgement of temperature. However, again, results were ambiguous. Bennett and Rey [3] found that wearing coloured googles did not have any effect on the judgement of thermal temperature. Whilst wearing goggles, within some limits, has similar effects as changing the illumination, the authors themselves speculated whether the "washed-out" impression that the goggles produced might explain the absence of an effect. Berry [4], likewise, did not find any impact of illumination in five different hues on the point when participants reported feeling unpleasantly warm; however, participants were engaged in a task that supposedly measured the impact of differently coloured light on driving performance. Hence, one might speculate that when focusing on an unrelated but engaging task, awareness of our thermal comfort state is reduced. This speculation is corroborated by the fact that temperature conditions at point of expressed discomfort were of such values[1] that virtually every person would be expected to feel uncomfortable, i.e. a very high value, whereas one would expect half the people to feel uncomfortable already at a much lower level. However, several studies reported that observers either judged thermal temperature to be higher when illuminations had a warm colour [74,24], or preferred illumination colours (e.g. bluish) that compensated the temperature (e.g. warm) as predicted by the hue- heat-hypothesis [9]. In all of these studies, illumination per se was altered (i.e. not via goggles but via room lighting), and in none of the studies, participants had to estimate the room temperature in degrees. Instead, subjective comfort ratings [9,74] and temperature evaluations of the room ranging from hot to cold [74] were obtained, or temperature preferences estimated as indicated by adjusting the thermostat setting [24].

To summarize, existing research is somewhat ambiguous regarding a relationship between colour and perceived temperature/thermal comfort. Three conditions seem to be associated with the absence of an effect of colour on thermal perception: having to judge a room's temperature in degrees as an outcome measure [30,61]; performing an engaging task [4], and manipulation of the colour of objects that are to be judged for their warmness [32,53]. Previous studied also suffered from methodological issues, such as insufficient control for varying luminance levels (e.g. Ref. [33,3]), not measuring temperature according to the standard BS EN ISO 7726 [38] (e.g. Ref. [61]), and not controlling for other factors known to impact on thermal comfort (e.g. Ref. [30]). Finally, none of the studies accounted for differences in ambient temperatures between session and/or participants in the analysis, even though acknowledging that there were such differences (e.g. Ref. [3]).

1.2. Introduction to thermal comfort

Thermal comfort is complex, and many factors impact on it that need to be considered when evaluating the hue-heat-hypothesis. In the literature related to thermal comfort, two very different approaches dominate: (a) the heat balance or predictive model of thermal comfort, and (b) the adaptive model of thermal comfort (for an overview, see Refs. [6,60]). In the heat-balance models, six factors predict the occupants' overall satisfaction with the thermal environment as expressed by the Predicted Mean Vote (PMV): (1) ambient air temperature (T_a), (2) mean radiant temperature (T_r), (3) relative humidity (RH), (4) air velocity (V_a), (5) metabolic rate (met), and (6) clothing level (clo) [39,Annex D,23]; hence, these factors need to be controlled for when studying thermal comfort. Note that illumination does not feature as a factor impacting on thermal comfort in existing predictive comfort models in the tradition of Fanger.

Numerous studies found that participants were satisfied with thermal conditions outside the range as predicted by the PMV [16]. These findings fed into the evolution of adaptive models of thermal comfort in which factors beyond the heat-balance of a body are of importance, such as previous and current climatic experiences [55]. One of the main characteristics of the adaptive model is that indoor thermal comfort is associated to both indoor operative temperature and prevailing mean outdoor temperatures [17]. Having control over the environment also impacts on comfort experience [59]. Again, illumination does not feature as an impact factor but it could be integrated via psychological adaptation which "describes the extent to which habituation and expectation alter one's expectation of and reaction to sensory stimuli" [17,p. 3].

Other impact factors on thermal comfort are gender, age, and weight. Thermal dissatisfaction is more often expressed in females than in males (e.g. Refs. [44,64]), and thermal comfort preferences can vary with age (e.g. Refs. [57,65]). Underweight participants have been shown to suffer more from cold extremities [54], and in general, weight and height are related to physiological parameters that in turn impact on thermal comfort (for an overview, see Ref. [35]).

[1] For details on the Temperature Humidity Indicator that was used in this study, refer to https://www.google.com/patents/US3124002. Accessed 17.06.2015.