Feeling the light? Impact of illumination on observed thermal comfort

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Introduction

The ‘Hue-Heat Hypothesis’ (HHH) states that light of wavelengths predominantly of the red end of the wavelength spectrum are felt as warm and those toward the blue end as cool(er). Manipulation of the ambient light colour could hence be a powerful tool for energy-saving in buildings if temperatures could be lowered under a reddish illumination in the heating season, or, conversely, be kept higher under bluish illumination in air-conditioned buildings. In the UK, space heating is responsible for about 53% of carbon emissions in domestic buildings, and for 46% of all carbon emissions in commercial and public buildings in which cooling and ventilation contribute another 7%; hence, the scope for energy saving is large.

However, whilst there is common agreement that blue stands for ‘cold’ and red for ‘warm’ - the colour coding of most bathroom taps as the prime example – research on the association between colour and thermal perception is less clear.

A series of studies have studied the Hue-Heat-Hypothesis, with about half finding an effect as hypothesized.

Mogensen and English (1926) asked subjects to judge which of two cylinders covered with one of six saturated coloured papers felt warmer. Red and purple were significantly less often judged as warmer than the other four colours, contrary to expectations.

Greene and Bell (1980) tested 72 students in rooms in which the walls were painted red, blue and white. Each student was exposed to one colour variation and one of four temperatures (18, 22, 29, and 35 °C). Amongst other tasks, students had to estimate the temperature of the settings, respectively. The estimations of temperatures did not differ significantly between settings.

Pedersen, Johnson, and West (1978) had per se identical rooms decorated and painted differently, i.e. with warm (red, orange, yellow), neutral (white), or cool (blue and green) hues. Using a between-subject design, 51 subjects estimated the temperature of the rooms. No significant differences between rooms emerged in temperature estimates.

Berry (1961) investigated whether the point at which people report experiencing heat discomfort depended on the colour of the illumination. He used five different lights, two "cool" colours (green and blue), two “warm” colours (yellow and amber), and white light. Subjects supposedly took part in a driving test in which it was supposedly important to know when subjects were too warm as that might interfere with driving performance. The colour of light did not impact on this judgement.

Bennet and Rey (1972) used yet another way of manipulating the colour experience: They provided participants with blue, red, or clear goggles. The investigators could not find observable correlations between hues and thermal comfort judgments.

Contrasting these null-results, the following studies all found an association between colour and thermal perception.

Johannes Itten (1961) showed that participants started to feel cold in a blue-green painted room at about 15 °C, but only at about 12 °C in a red painted room. Clark (1975) also tested thermal comfort in a design using painted walls. Employees of an air-conditioned factory reported feeling cold at 75 degrees F (~ 24 °C) when the walls of the cafeteria in the factory were painted in light blue. However, they were too hot at 75 degrees (~ 24 °C)when the same walls were painted orange.

Kearney (1966) exposed subjects to different combinations of hue, brightness, and temperatures (about 40°C, 16 °C, and a few degrees below zero, named hot, cool, and cold). Participants showed a higher preference for long wavelengths at cold temperatures, and for short wavelengths at hot temperatures.

Fanger, Breum, and Jerking (1977) used a within-subject design. In an environmental chamber, 88 subjects were exposed to two types of coloured light (extreme red or extreme blue) and two noise levels. One sessions lasted about 2 ½ hours. The ambient temperature was adjusted according to subjects' wishes. Subjects preferred a slightly lower temperature under the red ambient light than under the blue light; an effect of the magnitude of 0.4 °C. The physiological measurements of skin temperature, rectal temperature, and evaporative weight loss were not influenced by the light, and neither by noise.

A recent study varied colour temperature which is expressed in degrees Kelvin and ranges from about 1,800 K (light of a candle) to 15,000–27,000 K (clear blue poleward sky), i.e. from 'warmer' to 'cooler' light. Candas and Dufour (2005) exposed 48 subjects to a colour temperature of either 2700 K or 5000 K for two hours in "slightly warm environments" and asked them to judge their thermal comfort. Subjects preferred the cooler light; the effect was small but significant (~5 points on a scale from 0 to 100).

To summarize, existing research is ambiguous regarding a linkage between colour and perceived temperature / thermal comfort. The multitude of different ways of manipulating colour and response types complicate comparability between studies and drawing final conclusions. The positive findings of Fanger et al. (1977) and Candas and Dufour (2005) which warrant revisiting the Hue-Heat-Hypothesis, given that they are similar to how this effect could be used to realize energy savings, i.e. through varying illumination in a building.

We used an experimental approach in a climate chamber to test if light impacts on thermal comfort. The advantage of testing in a climate chamber was that research on thermal comfort shows that radiant temperature, air temperature, air velocity, and relative humidity impact on thermal comfort (in addition to level of clothing and metabolic activity); and the climate chamber allows exact manipulation of these parameters.

Subjects were exposed to either a 'warm' or 'cold' light while sitting in the climate chamber with temperatures decreasing from about 24 °C to 20 °C over the course of 60 minutes. To overcome limitations of self-report surveys, an observational design was used where the experimenter noted if and when participants put on additional clothing. We hypothesized that (a) under cold light, participants would put on more items of clothing than under cold light, and (b) under cold light, participants would put on clothes earlier than under warm light.

Methods

Participants.

Participants were recruited through the subject pool of University College London (UCL). The age range was limited to 18 to 35 years. The study was approved by the UCL Ethics Committee; all participants provided written informed consent prior to the study. Payment was £8/hour. The sample consisted of N = 32 participants (23 female, nine male). The average age was M = 23.5 (SD = 2.51).

Experimental design and set-up.

Testing was carried out in the climate chamber which is an enclosed room of about 2.60 x 3.80m in which temperature, humidity, and air velocity can be controlled. The chamber was partitioned in two in order to prevent the two participants tested concurrently seeing each other. The observer was sitting in front of the participants.

A between-subjects design was used. Participants were randomly assigned to either participate under the 'warm' light (2700 K), or the 'cold' light (6500 K). Illuminance at reading level was 550 lux at 2700 K, and 495 lux at 6500 K. The light setting hence constituted the independent variable. Each light setting was tested equally often in the morning and afternoon.

A LED-based ceiling light ('ChromaWhite' from Photonstar) was used, equidistant to both participants at a height of about 2.20m. Figure (1) shows the spectral composition of the light.

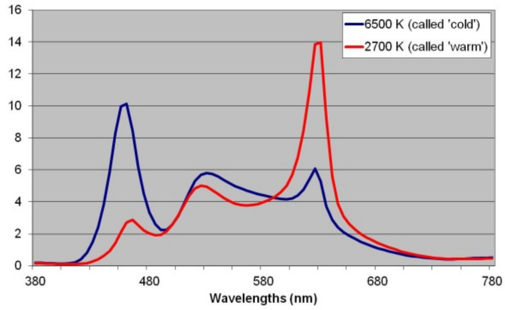


Figure 1. Normalized spectral composition for the 2700 K and 6500 K light.

Experimental procedure.

During recruitment, participants were told what to wear during the experimental session in order to keep the level of clothing identical across participants. In addition, they were instructed to bring a sweater / light jumper and a light jacket to the experimental session. Upon arrival, the participants were given information sheets, a consent form, and had to fill in a background survey about their age, gender, clothing, activity prior to testing, etc. This pre-testing period of about 20 minutes ensure a somewhat comparable rate of metabolic activity, i.e. 20 minutes of sitting still. The experimenter positioned the clothing and a blanket provided in the climate chamber in the same location for all participants.

Participants were then led into the climate chamber; and instructions summarized, i.e. to sit and read, and if they should want to, to put on additional clothing or use the blanket. The experimenter was equipped with a stopwatch and recorded when participants put on clothing, and what they put on. These observations formed the dependent variables. In detail, the dependent variables were: (1) total number of clothing item put on, (2) minutes in climate chamber when first item of clothing was put on, (3) minutes in climate chamber when second item was put on, (4) minutes in climate chamber when third item was put on, and (5) the type of clothing put on and its respective insulation level.

Results

Analysis of confounding factors.

Besides room temperature, relative humidity and air circulation, which were controlled during the experiment, other factors that might impact thermal comfort are metabolic activity, type of clothing, gender and the Body-Mass-Index (BMI). Hence, we first tested whether those factors differed between groups.

The reported metabolic activity was translated into 'met' values as given in Annex B of the EN ISO 7730:2005, separately for each of the four time periods enquired about. The values were then averaged across the four time periods. A *t*-test for independent samples showed that the metabolic activity over the last 10 minutes was not significantly different between the two experimental groups (M_{2700K} = 1.9; M_{6500K} = 1.7); neither was the aggregated value for metabolic activity (M_{2700K} = 1.8; M_{6500K} = 1.7).

The items of clothing subjects reported wearing were translated into a total score of 'clo' level as defined in Appendix C of the EN ISO 7730:2005. Each item was translated into its corresponding insulation value and those values were then summed up for each person. An independent samples *t*-test showed no significant difference in total clothing level between the two experimental groups (M_{2700K} = 0.59; M_{6500K} = 0.57)

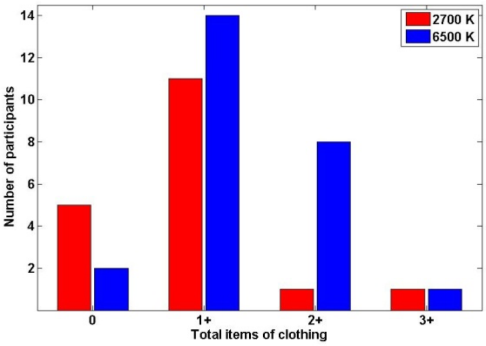
Whilst the gender balance was unequal in this study, females and males were equally distributed across the two lighting settings (2700 K: 5 males, 11 females; 6500 K: 4 males, 12 females), as shown by a Chi-Square test.

The BMI was calculated for each person. An independent samples *t*-test confirmed that the BMI was not statistically different in the two experimental groups (M_{2700K} = 21.2; M_{6500K} = 22.2).

As the two experimental groups did not differ in variables likely to impact on thermal comfort, they were not used as factors in further analysis[1].

Total items of clothing put on.

Figure 2 shows how many participants put on how many additional items of clothing. Note that the categories are inclusive; i.e. a participant who put on two items of clothing will be counted both for the "1+" and "2+" category.



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[1] Of course, these factors can impact thermal comfort but the effect would occur in both groups.

Figure 2. Total items of clothing put on under 2700 K ('warm') and 6500 K ('cold').

More participants put on extra clothing under the cold light than the warm light. Only one person put on 2 or more items under the warm light but nine persons under the cold light. The observation of less clothing needed under warm light was confirmed through statistical analysis. Since the Shapiro-Wilk test showed that the variable 'total_clothing' was not normally distributed; the non-parametric Mann-Whitney-U-Test was used to test for significant differences. We found a significant effect of lighting (U = 70.5, *p* = .019). More items of clothing were put on under the cold light than the warm light, supporting the first hypothesis.

There was no difference in what item of clothing participants used first.

Minutes in the climate chamber.

We analyzed if participants put clothing on after fewer minutes under the cold than the warm light. This analysis is somewhat problematic because it needs to exclude those participants who did not put on any clothing and hence ignores that some people would have put on clothing only after more than 60 minutes. The average time before putting on the first item of clothing was 37 minutes under warm light (N = 11) and 34 minutes under cold light (N = 14). This difference was not significant. For two or more items, analysis was not possible as one participant put on more clothing under the warm light (as opposed to 8 under cold light).

Discussion

Our study used an experimental design to test if apparent thermal discomfort, operationalized as putting on extra clothing at decreasing temperatures was impacted by the surrounding illumination. Participants put on significantly more items of clothing under cold light than warm light. The time when they put on extra clothing did not differ significantly between the two groups.

We conclude that the results show some support for the Hue-Heat-Hypothesis. Varying the illumination in a building could therefore be a tool for reducing energy consumption in buildings by off-setting changes in temperature and hence thermal comfort through changes in illumination. In particular for short-time power management applications, this could be of great benefit. The temperature range considered in this study is comparable to conditions in offices; a larger effect of light might be observed when lowering temperatures further; however, given the desired application in offices, the results might not be transferable into a real-world setting

Further research needs to ensure that the observed effect would hold up in a natural setting, and ensure that performance and mood are not impacted differentially by the two lights (both tested currently). In addition, the potential for energy savings need to be quantified by specifying the difference in degrees °C under different lights associated with identical comfort levels.

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