# Crossed effects of visual factors on human thermal response

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**Abstract.** Recently, the approach for studying human comfort indoors has been changing for a multi-domain framework once some studies have reported crossed effects between different comfort domains (i.e., thermal, visual, acoustic, and air quality). An example of crossed effects between comfort domains is the hue-heat hypothesis (HHH), referring to the possible association between lighting and the human thermal response. This paper presents a new investigation to verify the validity of the HHH. Several experiments were conducted in a test room under a fully controlled setting, combining two thermal (slightly cold and slightly hot) and three lighting conditions (blue, red, and white lights with nearly the same illuminance level). The experiments were divided into two parts, each one dedicated to a thermal setting. After acclimatisation, the participants were submitted to each colour of light for seven minutes under a constant air temperature. A total of 39 people participated twice in the experiment, each time in a different thermal condition, and before changing the colour of light, they answered a survey about their thermal sensation, thermal comfort, visual comfort, overall comfort, and perceived level of productivity. Answers were compared using statistical methods. The results did not allow to confirm the HHH, since no statistically significant differences were observed for thermal comfort and thermal sensation for the different colours of light. The only significant difference observed was for visual comfort in the slightly cold thermal condition, between red and white lights. In fact, the survey responses for visual comfort indicate that people preferred the white light. White light was also associated with better overall comfort assessment and perceived productivity in both thermal conditions, but the differences were not statistically significant. Further investigations should be performed under more thermally stressful environments and should also evaluate the physiological factors of participants as a thermal response instead of only subjective outcomes.

**Keywords.** Thermal comfort, multi-domain comfort, coloured lights, hue-heat hypothesis.
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## 1. Introduction

Indoor environmental quality can significantly influence the health, well-being, comfort, and productivity of building occupants [1]. Humans are simultaneously exposed to environmental stimuli associated with different domains, namely thermal, visual, acoustic, and air quality. Recently, the assessment of human comfort in indoor environments has been changing for the multi-domain approach since some studies identified combined and crossed effects between these domains [2]. Light, for instance, influences thermal comfort and other non-visual responses, like mood and alertness [3]. An example of the interaction between visual and thermal domains is the hue-heat-hypothesis (HHH) [4], which suggests that colours affect people's subjective thermal perception. In detail, light frequencies toward the red end of the visible spectrum are perceived as thermally warmer, while blue frequencies lead to a perception of a cooler environment.

Some studies tested the HHH, investigating the effects of lighting (coloured or with different correlated colour temperature (CCT)) on thermal responses, and confirmed this assumption [5,6]. Other researchers found significant differences only under specific thermal conditions [7,8] or during a particular season of the year [9], while some papers reported no significant associations between the lighting colours or CCT and the thermal perception [10,11]. Therefore, the reported results about the HHH are still unclear.

The ambiguity related to the results of the HHH testing supports the importance of further exploring this topic once the confirmation of the HHH would allow an enlargement of the temperature range found comfortable by occupants through the control of the lighting [7]. Considering that heating, ventilation, and air conditioning systems represent about 50% of building energy use [12], visual factors could be used to trigger varied thermal sensations in an energy-saving perspective.

In this context, the aim of this paper is to assess the influence of the colour of light on human thermal sensation and comfort. The HHH was tested, verifying if reddish lights could induce a hotter thermal sensation, and bluish lights could stimulate a colder thermal sensation. Then, 39 subjects participated in an experiment conducted in a fully controlled test room, being submitted to two thermal conditions (slightly cold and slightly hot) and three colours of light (blue, red, and white). The illuminance level for the three lighting conditions is nearly the same, then the only visual factor being altered during the experiments was the colour of light. Participants answered a survey about thermal sensation, thermal, visual, and overall comfort, and perceived level of productivity in each environmental condition, and the responses were compared through statistical techniques.

## 2. Research Methods

This article reports a multi-domain (thermal and visual) comfort investigation, aiming to identify whether the colour of light affects the human thermal perception. For this, it was planned an experiment associating different thermal settings and colours of light.

### *2.1 Experimental campaign*

The experiments were conducted in a test room under a fully controlled setting, in October and November 2021. The test room [13] is located at the Engineering campus of Perugia (Italy) belonging to the Cfa climate class according to Köppen Geiger [14]. The internal layout was specifically designed and built for reproducing an office environment (Figure 1). Inside this space, several environmental parameters, such as temperature, relative humidity, air velocity, surface temperatures, illuminance, and $CO_2$ concentration are continuously monitored every 30 seconds. The participants stayed seated during the whole procedure to simulate office activities.

**Fig. 1 –** Interior of the test room used in the experiments.

The tests combined two air temperatures, representing slightly cold and slightly hot conditions (i.e., 20 °C and 25 °C, respectively, since we were approaching the winter season [15]), and three colours of light (white (~540 lx), red (~587 lx), and blue (~563 lx)). The only source of light considered in the experiments was artificial (no daylight). The tests were separated into two parts, each one with a fixed thermal setting and varying colours of light. This approach was conceived because light colour is quickly adjusted indoors, easing the experiment procedure. The test room was pre-conditioned to guarantee a thermal equilibrium between the air and surface temperatures. Therefore, the air temperature was assumed equal to the mean radiant temperature, and so to the operative temperature, during the test.

Each part of the experiment lasted 41 minutes in total, and the thermal conditions were kept constant during this period. Figure 2 presents the experiment procedure.

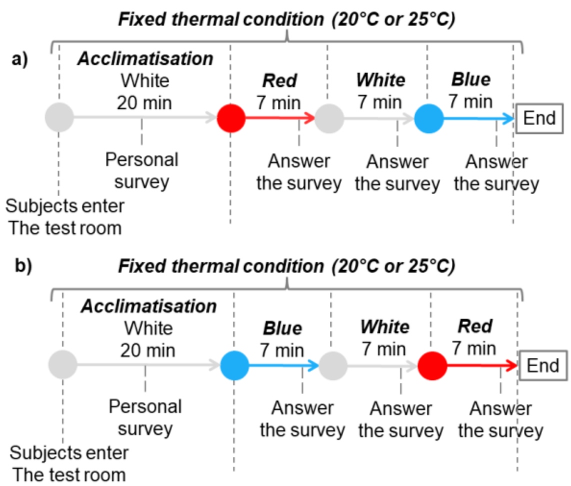


**Fig. 2 –** Experiment procedure when starting with red light (a) and blue light (b).

The first 20 minutes were dedicated to acclimatisation, with white light. During this stage, participants answered a personal survey (age, gender, height, weight, worn garments, and profession). The following 21 minutes were divided into three phases of 7 minutes, each one corresponding to a specific colour of light. In the last two minutes of every lighting condition, the participants answered a survey about their thermal sensation, thermal, visual and overall comfort, and perceived level of productivity. All questions were answered in a 5-point Likert scale.

A total of 39 subjects took part in the experiment and every person participated twice, each time dedicated to a thermal condition (at 20°C and 25°C). Aiming to minimise the bias of colours order, half of participants started the test with the red light, while the other half started with blue light. The order of the colours of light was unchanged in the two tests for the same participant.

As the test room where the experiments were performed simulates an office environment, the selection of participants were made considering people who usually stay in this kind of space in their daily life. The 39 subjects who participated in the experiment are students and young professionals who perform typical office tasks.

### *2.2 Statistical Analysis*

The first step of the analysis was the characterisation of the sample of participants. Data collected through the personal survey were used to describe the sample composition using descriptive statistics methods. The quantitative variables were evaluated by their mean, standard deviation, median, mode, skewness, kurtosis, minimum and maximum values, and 25, 50, and 75 percentiles. The qualitative variables were characterised in terms of percentage distribution.

In the end of the experiment, 234 answers (39 participants times two thermal conditions times three colours of light) related to thermal sensation and comfort, visual comfort, overall comfort, and perceived productivity were obtained. These responses were compared using the Friedman test [16], a non-parametric statistical test used to compare more than two paired samples. A non-parametric method was chosen because the survey's answers are ordinal variables. The significance level adopted in this study was 5%.

The aim of the study is to verify the crossed effects of colour of light on thermal perception, that is, the hypothesis tested is that people perceive the thermal environment differently when changing the colour of light and keeping the thermal condition constant. Therefore, responses were grouped by temperature, also to verify if the effects of colour of light on thermal perception are altered under different thermal settings. Then, the test was applied twice (two thermal conditions), each time comparing three samples related to the subjects' answers to the survey in every colour of light.

## 3. Results

### *3.1 Sample Composition*

The sample was characterised in terms of age, height, weight, body mass index (weight divided by the square of height), clothing insulation (calculated according to the guidelines of the ISO 7730:2005 [15], determined from the responses related to worn garments), gender, and profession. Table 1 presents the distribution characteristics regarding the quantitative variables. The distribution of clothing insulation involves the values of the two tests in which the subjects participated.

**Tab. 1 -** Descriptive statistics analysis of quantitative variables.

| | | Age | Height (m) | Weight (kg) | Body mass index ($kg/m^2$) | Clothing insulation (clo) |
|---|---|---|---|---|---|---|
| N | | 39 | 39 | 39 | 39 | 78 |
| Mean | | 22.44 | 1.73 | 66.66 | 22.29 | 0.83 |
| Median | | 23 | 1.73 | 65 | 21.67 | 0.85 |
| Mode | | 23 | 1.70 | 60 | 25.13 | 0.85 |
| Std. deviation | | 1.93 | 0.09 | 11.41 | 3.01 | 0.06 |
| Skewness | | -0.22 | -0.53 | 0.30 | 0.42 | -1.77 |
| Kurtosis | | 1.81 | -0.20 | -0.60 | -0.31 | 1.58 |
| Minimum | | 18 | 1.50 | 44 | 16.56 | 0.70 |
| Maximum | | 28 | 1.85 | 90 | 29.30 | 0.90 |
| Interval | | 10 | 0.35 | 46 | 12.74 | 0.20 |
| Percentiles | 25 | 22 | 1.65 | 60 | 20.46 | 0.85 |
| | 50 | 23 | 1.73 | 65 | 21.67 | 0.85 |
| | 75 | 23 | 1.80 | 75 | 24.47 | 0.85 |

Height and clothing insulation are less dispersed in relation to the mean (low standard deviations), while weight and body mass index samples have more spread-out values. Age is also concentrated around mean, which is expected since this was a criterion for the choice of the subjects. Height, weight, and body mass index were considered as approximately normally distributed because the skewness and kurtosis values between −1 and +1.

Gender and profession are qualitative variables, so they were described in terms of percentage distribution, as shown in Figure 3.

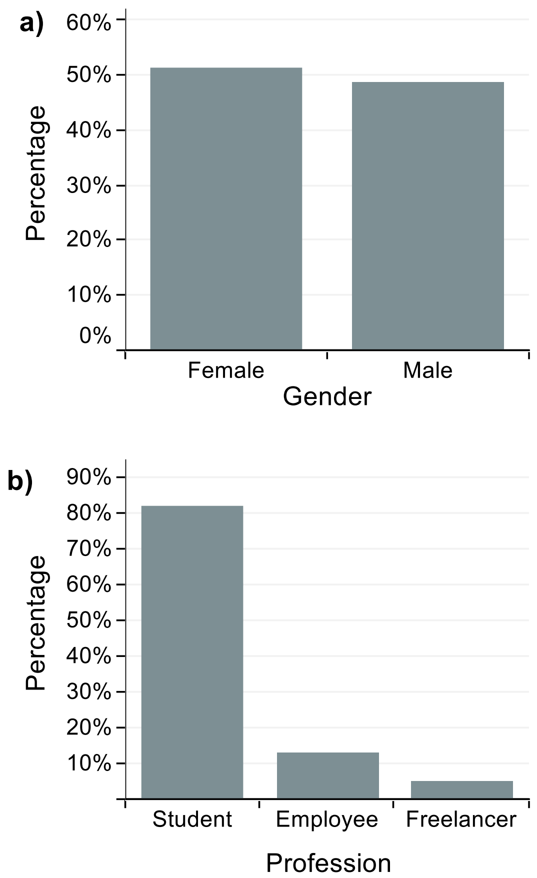


**Fig. 3 –** Sample description in terms of percentage for gender (a) and profession (b).

Participants are equally distributed among gender, following the same distribution as the local population [17]. Concerning the profession, as mentioned in Section 2.1, participants were selected according to their daily life activities. They are mainly students because this is the principal activity practiced by local people of this age [18].

### *3.2 Survey responses*

During the experiments, participants were asked about their thermal sensation; thermal, visual, and overall comfort; and perceived level of productivity, for each colour of light. No differences in answers were observed between genders for these questions.

Figure 4 presents the votes regarding thermal sensation separated by colour of light and thermal condition. At 20°C, the "hot" sensation is mainly associated with the red light. However, in this environmental condition, the same percentage of votes is observed for "cold" sensation, which contradicts the hypothesis tested that reddish lights induce a hotter sensation. Blue and white lights in this case represent the larger amount of "neutral" sensation. At 25°C, small differences are observed between red and blue lights on votes for "hot" and "very hot" sensation, which again goes on the opposite of the initial hypothesis that bluish lights provoke colder sensation.

Concerning thermal comfort, no differences in votes for blue and red lights were observed at 25°C, while at 20°C more votes associated to "comfortable" or "very comfortable" were reported in blue light. The white light is the one associated with the highest part of positive thermal comfort votes under the two thermal conditions. The same is observed for the answers related to overall comfort and perceived level of productivity: the highest number of "very comfortable" and "very productive" votes are related to the white light.

For visual comfort, it is important to highlight that even though the negative votes represent a small amount of the total, they are mainly associated to blue and red lights, while the highest part of "very comfortable" votes are associated with the white light.

### *3.3 Statistical Tests*

The survey responses were compared using the Friedman test to check if there is a difference statistically significant in their answers for different colours of light. Table 2 presents the *p* values obtained when applying the statistical test, for the two thermal conditions.

**Tab. 2 –** *p* values for the Friedman test.

| Question | Thermal condition | |
|---|---|---|
| | 20°C | 25°C |
| Thermal sensation | 0.389 | 0.090 |
| Thermal comfort | 0.128 | 0.153 |
| Visual comfort | 0.004 | 0.107 |
| Overall comfort | 0.123 | 0.708 |
| Productivity | 0.289 | 0.208 |

For a significance level of 5%, it was observed no statistically significant difference in answers for different colours of light, except for visual comfort at 20°C. For this case, a post hoc test (Nemenyi test) was applied, and it was verified that the difference is statistically significant only between white and red lights ($p = 0.010$).

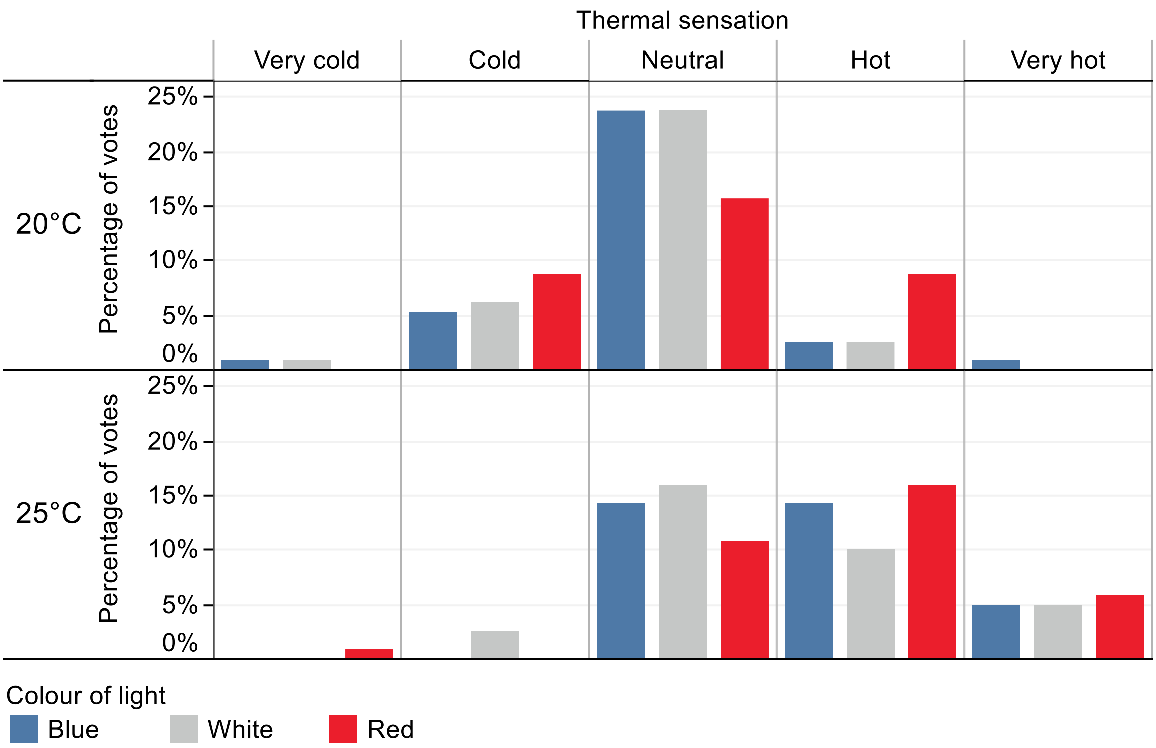


**Fig. 4 –** Survey answers regarding thermal sensation according to each thermal condition and colour of light.

Through this analysis, it was concluded that this specific segment of the population (young adults in their 20s) does not have their thermal sensation and comfort changed when modifying the colour of light and keeping the air temperature constant. Therefore, the initial hypothesis that a reddish light induces a hotter sensation, and a bluish light causes a colder sensation was not confirmed with this experiment. In fact, some participants reported a "cold" or "very cold" sensation even with red light (Figure 4). Moreover, changing the colour of light did not affect significantly the overall comfort and the perceived level of productivity of the participants for both thermal conditions.

The only aspect that presented some significant variation when changing the colour of the light was visual comfort, which is directly related to light. However, this was noted only for a specific thermal setting, slightly cold, that is close to the neutrality and thus without significant thermal disturbances, theoretically. In this thermally comfortable space, the coloured light could be more noticed by the subjects who could consider it a source of discomfort.

## 4. Conclusions

This paper presents an experiment that tested if colour of light could induce different thermal perceptions under fixed thermal settings in office environments. The sample of participants was formed by young adults that usually perform office tasks in their routines, and their perceptions were assessed through surveys.

No statistically significant differences were observed in thermal sensation and comfort reported by the subjects, opposing the initial assumption that red lights could induce a hotter sensation, and blue lights could provoke a colder sensation. Therefore, this study was not able to confirm the HHH, considering the specific group of the population under investigation. Furthermore, the negative votes for visual comfort are associated mainly with the red and blue lights, indicating that this group prefer the white light in this kind of environment. The variation is significantly different only in the slightly cold thermal condition.

The seven-minute exposure to each colour of light allowed carrying out the within-subjects experiment with a larger number of participants in a limited time. However, this interval could be considered short in view of people's long exposure to artificial lights during the day. The effect of long exposures should also be explored, taking into account a possible visual adaptation that could influence the thermal response of participants. Furthermore, the time of the day when the experiment was conducted should be explored, since some studies already reported significant differences in thermal perception with the time of the day [22].

Further investigations should be done in more uncomfortable thermal environments (too hot and too cold settings) to evaluate if colour of light could reduce the thermal stress under these conditions, and should involve other age groups. They could also include the investigation of physiological parameters of subjects as a thermal response.

Moreover, the productivity could be additionally assessed with psychological tests developed to evaluate specific cognitive functions like attention, concentration, and reaction time, that could be associated to productivity. Some examples are the Stroop test [19], the d2 test [20], and the Continuous Performance test [21].

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### *Data Statement*

The datasets generated during and/or analysed during the current study are not available because this is an ongoing project, but the authors will make every reasonable effort to publish them in near future.