Thermal comfort and visual interaction: a subjective survey

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Abstract. The application of the human factors’ principles stated the need for rethinking the indoor built environment design which should also conjugate the binomial energy saving-Indoor Environmental Quality (IEQ). This means that the optimization of a single IEQ component should also account for possible antagonistic or synergic effects. The hue-heat hypothesis is based on the idea that light and colours can affect the thermal perception. Particularly, spectral power distributions of light shifted to short wavelengths seem to promote a cooler thermal perception and the vice-versa. Several efforts have been made in the past to characterize the effect of the colour of light on thermal comfort, with experiments giving conflicting results mainly due to a bad control of lighting and microclimatic parameters and to the use of not robust measurement protocols. To verify the hue-heat hypothesis, in this study 81 subjects have been exposed to two different lighting scenarios characterized by warm and cool light at a fixed task illuminance value (300 lx) under winter thermo-hygrometric conditions in a special test room provided with white-tuning LED sources. Preliminary findings seem to confirm that warm light results in a warmer thermal sensation with a potential improvement of comfort conditions.

1. Introduction

Only in recent years, the application of the human factors’ principles resulted in a new way of conceiving the built environment design [1]. Indoor environments should be liveable, comfortable, safe, productive [2] with low energy costs [3] and their design should be compliant with sustainability requirements [4]. These are the reasons why the overly stringent rules on the energy saving account for the binomial energy saving-IEQ [3]. This implies that the optimization of a single IEQ component should also consider possible synergic or antagonistic effects. Concerning thermal perception, despite it seems almost accepted that thermal comfort can be affected by stimulations of non-tactile modalities, relatively few investigations have succeeded in delineating non-tactile stimulations as the visual ones [5]. A common belief is that lights or surfaces, whose dominant frequencies are toward the red end of the visible spectrum, are felt as warm and those toward the blue end are felt as cool. This hypothesis - known as hue-heat hypothesis (HHH) involves the concept of one set of environmental parameters, namely thermal comfort, interacting with another, namely environmental chromatic characteristics.

As stressed by Candas and Dufour [6] in a review devoted to the multisensory interactions on the thermal perception, several efforts have been made in the past to characterize the effect of light on thermal comfort with experiments giving conflicting results. In 1961, Berry [7] studied the effect of the colour of illumination on 25 volunteers unaware of the aims of the study. The test room was equipped with a lighting system able to reproduce light in five different shades: amber, yellow, white, green and blue. However, the subjects did not show changes in the thermal perception as a function of the colour of the light. Similar results were found by Bennet and Rey [8]. In their investigation they made subjects rate thermal comfort while wearing red, blue and clear goggles while air conditions were “comfortable” and wall temperatures were varied from about 16 °C to 38 °C and back. The analysis of the subjects’
thermal comfort perception revealed no major hue effects or interactions. This is also the case of a most recent investigation carried out in Finland under laboratory conditions (at illuminance $E=1000$ lx) on a sample of 16 subjects [9].

Evidences to support the hue-heat hypothesis are the studies carried out by Itten [10] and Clark [11] who found that thermal comfort was significantly impacted by wall colour, with participants feeling colder in blue/blue-green room. Similar results were also found by Fanger, the most influential pioneer of thermal comfort issues [12]. In a paper dated 1975 [13], he found that a slightly lower ambient temperature (0.4 °C about) was preferred in extreme red light compared to extreme blue light ($E=150÷190$ lx). Other studies in aircraft cabin [14] revealed that indoor temperature was perceived as being different depending on the colour of the lighting ($E=130÷200$ lx). Under yellow light conditions, room temperature was felt to be warmer than in blue light. As a support to the HHH, Huebner et al. [15] found that people put on significantly more items of clothing under cool light than warm light. In recent studies, based on a series of empirical investigations in Sri Lanka, Hettiarachchi et al. [16] discovered that incorporating red colour in interiors of cool tropical uplands induced a comparatively warmer thermal perception where the reverse was true in hot, humid coastal areas. Further evidences for HHH come from Golasi et al. studies [17], who also suggested possible variations in air temperature values of 1.3 °C when cool light is applied.

According to the recent investigation by Toftum et al. [18], it is still unclear whether the colour of light affects the thermal sensation only under microclimatic conditions close to thermal neutrality. Particularly, on a wide sample of subjects exposed to different lighting scenarios ($E=1000$ lx) by operating on the Correlated Colour Temperature (CCT) of LED, they concluded that CCT was associated with thermal sensation at the thermally neutral condition, but not when subjects felt slightly cool or slightly warm. This is also for alertness according to previous studies [18]. As also stressed by Huebner et al. [15] and Wang et al. [19] existing research is ambiguous regarding the association between colour and thermal perception mainly due to different ways of manipulating the different lighting [20, 21] and microclimatic conditions (see table 1). Moreover, most literature surveys also suffered from methodological issues, such as a poor control of microclimatic and lighting parameters and a lack of robust protocols for objective and subjective investigations.

To verify the HHH, and exploit potential energy saving related to the control of the perceived thermal sensation by means of the colour of the light, this paper will be devoted to a combined microclimatic and subjective investigation carried out in a special mechanically conditioned test room provided with white-tuning LEDs. In this preliminary step of investigation, the analysis will be focused on winter conditions and two different light scenarios.

2. Method
2.1 The lighting setup
Experimental tests have been carried out at the Laboratory of Photometry and Lighting of the Department of Industrial Engineering of the University of Naples Federico II (Italy) in a L-shaped room composed of two different rectangular parts (figure 1). The wider space (marked in red in figure 1) is a neutral environment equipped with a false ceiling provided with different light sources. Here, three white curtains cover the perimeter walls and a fourth, once closed, divides the two parts of the room. A desk and a chair are here located. The reflectances of architectural surfaces, referred to the D65 illuminant and measured by means of a Konica Minolta CM 2600d spectrophotometer vary in the range from 80.2 to 93.2%. In the smaller space (marked in blue in figure 1) the DALI (Digital Addressable Lighting Interface) unit used to control the luminaires is located. It consists in a touch panel allowing to easily set different light scenes, by varying luminous flux emission and Correlated Colour Temperature of luminaires (CCT). White tuning LEDs with the following characteristics (declared by the manufacturer) have been used: luminous flux= 4280 lm, power = 51 W, Colour Rendering Index (CRI) > 80. For the purpose of this investigation two light scenes have been considered with a CCT of 3000 K and 6000 K, respectively (both characterized by measuring the normalized spectral power distribution).
Figure 1. Plan of the test room (with dimensions in meters). Legend: P_L (measurement point of lighting parameters), P_M (measurement point of microclimatic parameters).

For both CCTs, luminaires luminous flux was regulated so that the corresponding illuminance at the work-plane was equal to about 300 lx, consistently with a reading task as claimed by the EN 12464-1 Standard [22]. To verify that, the illuminance was measured at the point P_L, located on a desk -distance from the floor: 0.75 m- (see figure 1) by means of a Konica Minolta T-10A luxmeter.

2.2. The thermo-hygrometric setup
The measurement of the physical parameters affecting the thermal sensation (global and local) has been carried out by means of a Comfort Data Logger INNOVA 1221 provided with sensors for the air temperature, the plane radiant temperatures, the air velocity, the dew point and the floor temperature. Sensors were placed on a tripod near the position occupied by the subjects (P_M as in Figure 1). All sensors were compliant with the ISO 7726 accuracy requirements [23]. The measurements (recorded at different height from the ground) involved the main physical variables [24] responsible for the thermal sensation. The calibration of the test room has been carried out by settling the HVAC system in the range from 18 °C to 25 °C and then measuring all physical quantities each minute for 15 minutes. The procedure has been repeated three times to verify the attainment of steady-state and homogeneous environmental conditions. As summarized in table 1, the low SD values of the physical quantities demonstrate the careful control of the microclimatic conditions and ensure negligible effects on the subjective survey.

Table 1. Values of microclimatic parameters recorded 60 cm above the floor for a winter set point temperature of the test room equal to 20 °C (81 runs). SD = Standard Deviation.

| Parameter                  | Mean | SD  |
|----------------------------|------|-----|
| Air temperature $t_a$, °C  | 20.3 | 0.2 |
| Mean radiant temperature $t_r$, °C | 20.8 | 0.0 |
| Air velocity $v_a$, m/s    | 0.01 | 0.00|
| Relative humidity RH, %    | 53.9 | 2.7 |

2.3 The subjective survey
2.3.1. Procedure. 81 volunteers aged between 18 and 35 (41 females) took part in the experiments. None of them had a background in the lighting field or revealed health or psychological problems. Subjects were led one by one in the test room and they were invited to fill a preliminary section of the questionnaire with general information (e.g. age, height, weight, nationality, worn clothing at the moment of the survey, possible health problems). Then they were asked to stay inside the test room for 10 minutes to adapt to the environmental conditions. During this phase they were also invited to play word puzzle. This served as a distraction with respect to the surrounding environment in such a way that they would not have had memory of it in the next test. The number of found words has been used as
indicator of ability, in order to verify if the CCT influences concentration capacities. For this purpose, the world-puzzle was considered appropriate since it is a rather spread game, it requires a concentration effort, but not too specific skills, so it can be played by all participants regardless of their cultural background. After the subjects experienced the test room conditions, a sound signal was given to prompt them to fill a questionnaire focused on the thermal perception. After completing the questionnaire, the subjects were invited to leave the test room for 10-15 minutes in order to change the light scene. At this point the subjects were accompanied again in the test room, and the procedures of adaptation and administration of the questionnaire (game included) were repeated. Basic clothing insulation values, corrected by the effects of movements and air action [25-27], were 0.91±0.25, 0.80±0.14 and 0.85±0.20 clo for females, males and the overall sample, respectively.

2.3.2. The questionnaire. A special questionnaire designed with the assistance of a team of psychologists and doctors and specifically adapted to make it fast to be completed has been administered to each subject [28]. The questionnaire is divided into two sections: personal information and thermal comfort. The questions have been formulated in compliance with the recommendations of ISO 10551 [29] and concern the thermal status in terms of perception, evaluation and preference. Further three questions concern humidity, draughts and playing ability. In the present investigation the following parameters will be considered:

- the Thermal Sensation Vote TSV on the typical 7-points scale [29] from -3 (cold) to +3 (hot);
- the evaluation vote EV expressed on the scale from 0 (comfortable) to +3 (very uncomfortable);
- the preference vote PV expressed on the scale from -3 (much cooler) to +3 (much warmer);
- the humidity vote HV expressed on the scale from -1 (humid) to +1 (dry);
- the number of found words as indicator of playing performances.

Statistical analyses have been carried out by means of the ANOVA test performed by a MathWorks Matlab script and expressed in terms of p and F values. Cut-off value for significance tests has been fixed at 0.10 as usual in this kind of investigations [30].

3. Results and discussion
Based upon data summarized in table 2, for the light scene at 3000 K, the thermal sensation assessed by questionnaires reveals slightly warm conditions with TSV mean values equal to 0.60, 0.87 and 0.74 in case of females, males and the overall sample, respectively. In the presence of cool light (6000 K) the thermal sensation recorded form questionnaires shifts towards a cooler sensation with a reduction of the TSV value of about 4-5 decimals on the ASHRAE scale. It is noteworthy to stress that despite Toftum et al. results [18] and similarly to Wang et al. [19], this study verifies the association between CCT and the thermal sensation under slightly warm conditions. A reasonable explanation of this conflicting findings [9] could be the choice of the illuminance values which is one of the major issues when different literature studies are compared. In fact, unlike Danish team who worked at 1000 lx (a common value for precision works considering some industrial activities or for examination and treatment rooms in several health care applications) and similarly to Wang et al. investigation [19] the present study has been carried out at 300 lx which is a typical value for most common educational tasks [22]. The improvement of comfort conditions due to the application of cool lights appears consistent with judgments on the evaluation and perception scales. Cool light results in a reduction of the EV value (people feel more comfortable under cool light) and in a simultaneous increase of the preference vote (in the presence of cool light people prefer warmer conditions). Notwithstanding this, the differences in EV and PV votes under the two light scenes are not statistically significant (p>0.10). Finally, no correlation between CCT, air humidity perception and game performances have been found and no discussion or comparison with other studies can be provided. This is because the association of CCT with humidity perception has not been investigated in the past. Moreover, in the scientific literature, relatively few studies (carried out in too much heterogeneous conditions of lighting with inconsistent conclusions [31]) deal with the effect of CCT on performances. However, cool light seems to promote the alertness under thermal neutrality conditions [18] and favours computer-based and paper-based tasks [32].
Table 2. Statistical analyses from subjective investigation. (W) light scene at 3000 K, (C) light scene at 6000 K. SD=Standard Deviation. Significant outcomes (p<0.10) in bold.

| Parameter | Females | Males | Overall |
|-----------|---------|-------|---------|
|           | (W)     | (C)   | (W)     | (C)     | (W)     | (C)     |
| Mean TSV  | 0.60    | 0.23  | 0.87    | 0.41    | 0.74    | 0.32    |
| p (F)     | 0.082 (3.12) | 0.016 (6.10) | 0.0033 (8.92) |
| Mean EV   | 0.58    | 0.46  | 0.90    | 0.59    | 0.70    | 0.51    |
| p (F)     | 0.278 (1.19) | 0.155 (2.07) | 0.076 (3.20) |
| Mean PV   | -0.71   | -0.42 | -0.69   | -0.45   | -0.70   | -0.43   |
| p (F)     | 0.190 (1.75) | 0.464 (0.54) | 0.138 (2.22) |
| Mean HV   | 0.20    | 0.20  | 0.10    | -0.05   | 0.15    | 0.07    |
| p (F)     | 0.295 (1.11) | 1 (0.00) | 0.450 (0.57) |
| Number of words | 25.4    | 26.5  | 20.5    | 22.4    | 22.9    | 24.3    |
| p (F)     | 0.356 (0.86) | 0.202 (1.65) | 0.145 (2.15) |

4. Conclusions

In a general context where the attainment of energy saving goals (e.g. as in nZEB) has to be consistent with high IEQ levels, the optimization of comfort components (e.g thermal or visual) cannot ignore possible mutual interactions or negative effects on energy costs. In this paper the hue-heat hypothesis, based on the idea that light and colours can affect the thermal perception, has been investigated. Based on this assumption, changing light characteristics could help in improving thermal comfort for the occupants by increasing warmth (cold) sensation during winter (summer) and consequently it is possible to operate on the set-point temperature of HVAC systems in order to reduce energy consumption. Based upon results obtained in a special mechanically conditioned test room provided with white-tuning LED sources, we can confirm that, under winter conditions, cooler light (6000 K) induces a shift of the thermal sensation toward cold. Concerning the thermal preference and the evaluation of thermal comfort conditions, in the presence of cool light a warmer microclimate is preferred, and better comfort levels are experienced, but no statistical differences have been found, probably due to a thermal sensation relatively close to the neutrality. The results of this preliminary investigation will be integrated with further analyses addressed to verify possible effects of lighting parameters (e.g. illuminance and/or other CCT values) under different microclimatic conditions (e.g. near thermal neutrality or cold discomfort). Additional studies will be carried out on a wider and heterogeneous sample of interviewed also considering other human factors. Finally, further efforts will be addressed on the assessment of potential energy savings for heating and cooling obtained by operating on the CCT of the lighting system.

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