Hue-Heat Hypothesis: A Step forward for a Holistic Approach to IEQ

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Abstract. For many years different human factors contributing to the IEQ have been studied separately. Concerning thermal perception, despite it is almost accepted that thermal comfort can be influenced by concomitant stimulation of non-tactile modalities, relatively few investigations have succeeded in delineating non-tactile stimulations as the visual ones. The hue-heat hypothesis is based on the idea that, when spectral irradiance pattern at the observer's eye shows a great amount of short wavelengths, the space is perceived as cooler. Conversely, when long wavelengths are predominant, the space is perceived as warmer. This means that operating on light characteristics could help in improving thermal comfort for the occupants with possible energy savings obtained by acting on the set-point temperature of HVAC systems. To verify this hypothesis, this paper will deal with a subjective investigation carried out in a special mechanically conditioned test room equipped with white-tuning LED sources. Investigated subjects have been exposed to two different light scenes consisting of warm (3000 K) and cool light sources (6000 K) at a fixed task illuminance value. Preliminary results seem to demonstrate that cool light is effective in shifting to cool the perceived thermal sensation with a general increase of people under neutral conditions.

1 Introduction

Only in recent years the application of the human factors' principles stated the need for rethinking the whole indoor built environment design [1] which should conjugate low energy costs with high IEQ [2] (as a result of thermal, acoustic and visual comfort, and indoor air quality) and sustainability requirements [3,4].

IEQ strictly affects the overall building energy performances – as expressed again in the 2018/844 European Directive [5] – and it exhibits an antagonistic relationship with respect to the energy saving requirements. This means that the optimization of a single IEQ component should also consider possible antagonistic or synergic effects with the other IEQ components. This is also to reduce the onset of related illnesses and to optimize people's performance [6, 7].

Concerning thermal perception, despite it seems to be a common belief that thermal comfort can be influenced by concomitant stimulation of non-tactile modalities, relatively few investigations have succeeded in delineating non-tactile stimulations as the visual ones. The belief that colour can impart such effects as apparent warmth is widespread and ancient [8]. A popular hypothesis is that lights or surfaces, whose dominant frequencies are toward the red end of the visual spectrum, are "warm" and, those toward the blue end, are "cool". This is the concept of the hue-heat hypothesis [8, 9].

As stressed by Candas and Dufour [9] 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 the light colour on thermal comfort [10, 11], with experiments giving conflicting results. From this perspective, preliminary studies on the interaction between the light colour and the thermal sensation carried out by Fanger in the 70's sound almost astonishing. Despite he found in 16 subjects that a slightly lower ambient temperature (0.4 °C about) was preferred in extreme red light compared to extreme blue light, he concluded that "did not seem to have any practical significance on man's thermal comfort" [10].

In addition, it is still unclear whether the colour of light affects the thermal sensation only under microclimatic conditions close to thermal neutrality as recently investigated by Toftum et al. [12]. Particularly, on a sample of 44 subjects (16 females) exposed to different lighting scenarios by operating on the Colour-Correlated Temperature (CCT) of LED sources at three levels of operative temperature (19, 22 and 27 °C), they concluded that CCT was associated with thermal sensation at the thermally neutral condition, but not when subjects felt slightly cool or slightly warm.

As also remarked by Huebner et al. [13] and by Wang et al. [14] in two more recent papers, existing research is ambiguous regarding the association between coloured light/indoor surfaces and thermal perception. In addition, the different methodologies and protocols adopted in different researches complicate the comparability between studies and the ability to draw final conclusions [13]. This is especially true because previous studies also suffered from methodological

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issues, such as insufficient control of illuminance levels, microclimatic parameters according to the Standards in the field and other factors affecting thermal comfort [14].

To verify the hue-heat hypothesis, this investigation will be focused on the analysis of preliminary results obtained by a combined microclimatic and subjective investigation carried out in a special mechanically conditioned test room provided with white-tuning LED sources under winter conditions and with two different light scenes.

2 Methods

2.1 Test room lighting characterization

Tests were performed in the Photometry and Lighting Laboratory of the Department of Industrial Engineering of the University of Naples Federico II (Italy). It is an Lshaped room composed of two different rectangular parts. The wider space (see figure 1 on the top) is equipped with a false-ceiling, where different light sources are installed. Among these sources there are the two recessed LED luminaires used for the experiment.



Fig. 1. Measured plan of the test-room.

This area is a neutral environment: three white curtains cover the perimeter walls and another one, once closed, divides the two parts of the room. A desk and a chair are here placed. In the smaller space (see figure 1 on the bottom) there is the DALI (Digital Addressable Lighting Interface) control unit necessary to manage the luminaires. It consists in a touch panel allowing easily setting different light scenes, by varying luminous flux emission of luminaires and their Correlated Colour Temperature (CCT).

LEDs used in this investigation were white-tuning ones, which allow to change CCT in the range 3000 K-6000 K. According to the technical sheet provided by the manufacturer, luminaires characteristics are the following: luminous flux= 4280 lm, power = 51 W, Color Rendering Index (CRI) > 80. For the experiment two light scenes were set: Scene 1 characterized by 3000 K CCT and Scene 2 characterized by 6000 K CCT. Figure 2 reports normalized spectral power distributions of the luminaires when CCT is set at 3000 K and 6000 K respectively. They were measured by means of a Konica Minolta CS-2000 spectroradiometer.



Fig. 2. LED normalized spectral power distribution.

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 [15]). To verify that, the illuminance was measured at the point P1 (see Figure 1) by means of a Konica Minolta T-10A luxmeter.

2.2 Test-room microclimatic characterization

The microclimatic characterization of the test room has been carried out by measuring all physical parameters affecting the thermal sensation (global and local) by means of a special 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. In addition, three HOBO U12 Temp/RH/2 sensors for the measurement of air temperature and relative humidity have been used. All sensors were compliant with ISO 7726 accuracy requirements [16]

The measurements were carried out following a special and robust protocol designed consistently to the International Standards in the field [17] and involved the main physical variables affecting the thermal sensation [18]:

- the air temperature at three heights: 0.1 m, 0.6 m, 1.1 m;
- the air velocity at three heights: 0.1 m, 0.6 m, 1.1 m;
- the dew point temperature at 0.6 m;
- the six plane radiant temperatures at 0.6 m;
- the floor temperature.

Sensors have been installed on a tripod (see figure 3) placed close to the occupant as prescribed by ISO Standard 7726 [16].



Fig. 3. Datalogger and sensors (placed near the occupied position) used for the calibration of the test room and the measurements campaign.

The calibration of the test room has been carried out by setting the HVAC system (a split unit by AERMEC) in the range from 18 °C to 25 °C and then measuring all the physical quantities each minute for 15 minutes. The procedure has been repeated three times to verify the attainment of steady-state conditions and the homogeneity of environmental conditions was preliminarily verified by measuring the physical quantities in different positions.

Data summarized in table 3 show how microclimatic conditions of the whole experimental campaign are typical of quite uniform conditions as confirmed by the very close values of the air temperature and mean radiant temperature. In addition, the low SD values of the four physical quantities demonstrate the careful control of the microclimatic conditions with negligible effects on the subjective survey.

2.3 Experimental runs

2.3.1 Experimental procedure

81 subjects aged between 18 and 35 (41 females and 40 males) took part in the experiments. None of them had a background in the lighting field or revealed health or psychological (e.g. anxiety or stress) problems.

Subjects were led one by one in the test room (settled at 20 °C in this investigation) and they were invited to fill a short questionnaire with general information (e.g. age, height, weight, nationality, possible health problems). Then they were asked to stay inside the testroom for a time of 10 minutes to adapt to the environmental conditions. During this short period, they were also invited to play a 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.

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 having completed 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 were repeated.

Table 1. Summary of microclimatic parameters value recorded
0.60 m above the floor for a set point temperature of the test
room equal to 20 °C (81 runs). SD = Standard Deviation.

Quantity	MEAN	SD
Air temperature t_a , °C	20.3	0.2
Mean radiant temperature t_r , °C	20.8	0.0
Operative temperature t_o , °C	20.6	0.1
Air velocity v_a , m/s	0.01	0.00
Relative humidity RH, %	53.9	2.7

2.3.2 Questionnaire description

A special questionnaire designed with the assistance of a team of psychologists and doctors [19] has been administered to each interviewed and specifically adapted to make it fast to be completed.

The questionnaire consists of two sections:

- personal information. In this section subjects have to describe their clothing at the moment of the survey;
- thermal comfort. The questions of this section have been formulated in compliance with the recommendations of ISO 10551 Standard [20] and deal with the thermal status in terms of perception, evaluation and preference scale as showed in figure 4.

The questions also deal with humidity and thermal preference. A final question is focused on the possible effect of environmental conditions on the playing ability (not discussed here).

In the present investigation only the answer to the thermal perception (overall thermal state) has been considered. It is expressed in terms of a Thermal Sensation Vote (TSV) on the typical 7-point scale [18, 21] from -3 (cold) to +3 (hot).

1. How are you feeling now?	
	Hot 🗖
	Warm 🗖
	Slightly warm□
	Neutral
	Slightly cool
	Cool 🗆
2. Do you find this?	Comfortable 🗖
	Slightly uncomfortable
	Very uncomfortable
3. How would you prefer to be now?	
v i	Much warmer
	Warmer 🗖
	Slightly warmer
	Neither warmer nor cooler \Box
	Slightly cooler
	Cooler 🗆
	Much cooler□
4. Do you feel draughts?	
4.1. If yos how do you feel droughts?	NOL
4.1. If yes, now do you reef draughts.	Pleasant 🗖
N	either pleasant nor approving
	Annoving
5. How do you feel air (humidity)?	-5 5
	Dry 🗖
	Neither dry nor humid
	Humid 🗖
6. Did environmental conditions create probler	ns in playing words?
	YES 🗆
	NO 🗆

Fig. 4. The section of the questionnaire devoted to the thermal comfort assessment.

2.3.3 Statistical analysis

To verify the significance of the hue-heat hypothesis from subjective investigations, the well-known 2-tailed t-student test has been used [22]. In particular, by means of special Matlab functions, the following parameters were calculated:

- the 2- tailed Student's t-distribution $P(T \le t)$;
- the 2-tailed inverse of the Student's t-distribution $P(\mu)$ by assuming a statistical significance μ =0.10;
- the confidence $1-P(T \le t)$.

To verify that the differences among the samples were not related to the randomness, the occurrence of the condition $P(T \le t) \le P(\mu)$ has been finally checked.

2.3.4 Thermal comfort indices calculation

To allow the calculation of the thermal comfort indices [18], personal parameters as the metabolic rate and the clothing insulation have been evaluated according to the ISO 8996 [23] and the ISO 9920 [24] Standards, respectively. The metabolic rate has been fixed at 1.3 met consistently to sedentary activities [19, 23], whereas basic clothing insulation values were evaluated from questionnaires (see table 2) and corrected by the effect of air velocity and body movement [24, 25].

Finally, the calculation of PMV and PPD indices, required for the objective assessment of overall thermal comfort conditions according to the ISO Standard 7730 [18], has been carried out from measured values by means of the TEE package [26, 27]. This is a special software devoted to the assessment of the Thermal

Environment in agreement with the whole International Standards devoted to the Ergonomics of the Thermal Environment.

Table 2. Basic clothing insulation values with standarddeviation expressed in clo (1 clo = $0.155 \text{ m}^2\text{K/W}$) measured onthe investigated sample.

Females	Males	Overall
0.93±0.25	0.80±0.14	0.86±0.20

3 Results and discussion

The results of the subjective investigation in terms of thermal perception are reported in tables 3 and 4 and in figure 5. In table 3 the PMV values calculated from the instrumental surveys and the real clothes worn by each interviewed have been also reported.

Data summarized in table 3 seem to confirm the hueheat hypothesis for the sample of investigated subjects, being the thermal sensation votes recorded for cool light conditions (6000 K) systematically lower than those observed in case of warm (3000 K). In addition, these differences have not to be attributed to aleatory phenomena, but are statistically significant as confirmed by the verification of the t-test $P(t\leq T) < P(\mu=0.10)$ for the overall sample and for each gender.

 Table 3. Summary of TSV from subjective investigation,

 comparison with PMV values obtained by the objective survey

 and main statistical parameters. (W) light scene at 3000 K, (C)

 light scene at 6000 K. SD=Standard Deviation.

	Females		Males		Overall	
Quantity Light scene						
	(W)	(C)	(W)	(C)	(W)	(C)
Mean TSV	0.60	0.23	0.87	0.41	0.74	0.32
SD	1.01	0.73	0.83	0.82	0.92	0.78
PMV	-0.25		-0.34		-0.32	
SD	0.37		0.23		0.30	
t-test results						
$P(T \le t)$	0.0691		0.0175		0.0032	
P(µ=0.10)	1.6706		1.6676		1.6567	
Confidence	93.1%		98.3%		99.	7%

Despite Toftum et al. [12] and similarly to what found by Wang et al. [14] our findings seem to demonstrate that CCT is associated with thermal sensation even under incipient warm discomfort conditions. Particularly, with reference to the sample as a whole, for the light scene at 3000 K, the thermal sensation by questionnaires is typical of slightly warm conditions (mean TSV=0.74 on the edge of class C comfort zone [18]) with a percentage of persons who voted a TSV \geq 1 equal to 59% (see table 4). In the presence of cool light (6000 K) mean TSV decreases to 0.32 and the percentage of those who felt slightly warm or warm decreased to 40%. In addition, the percentage of respondents under neutral conditions and those who felt slightly cold increased from 34 to 46% and from 5 to 14%, respectively.

A reasonable explanation for the disagreement with Toftum et al.'s findings [12] could be the choice of the illuminance rate. Unlike Danish team who worked at 1000 lx (a common value for health care or special industrial tasks) and similarly to Wang et al. investigation [14], the present study has been carried out at 300 lux which is a typical value for some educational tasks [15].

Table 4. Percentage of persons who voted a single option tothe question on the thermal sensation of the ASHRAE scale(How are you feeling now?). (W) light scene at 3000 K, (C)light scene at 6000 K.

	Females		Males		Overall	
Sensation	Light scene					
	(W)	(C)	(W)	(C)	(W)	(C)
cold	0	0	0	0	0	0
cool	3	0	0	0	1	0
slightly cool	9	14	3	13	5	14
neutral	34	51	33	41	34	46
slightly warm	34	31	38	38	36	35
warm	20	3	26	8	23	5
hot	0	0	0	0	0	0

According to several literature studies [12, 28, 29, 30], that seem to confirm a certain gender related perception of thermal conditions, resulting in a high sensitivity of women to low temperatures [28, 29], this investigation has revealed a more pronounced effect of colour temperature on women's thermal perception. Based upon data in table 4, in case of warm light 54% of the women (64% of the men) voted warm o slightly warm with 34% of the respondents under neutral conditions (33% for men), whereas under cool light conditions the percentage of the women who voted TSV \geq 1 decreased to 34% (46% in case of the men). Consequently, the percentage of the women who felt neither cold nor warm increased from 34 to 51% (from 33 to 41% in case of men).

Finally, data in table 3 highlight a certain inconsistency between the subjective investigation by questionnaires and the objective assessment carried out by means of the PMV index. Particularly, TSV values obtained by subjective analysis were systematically positive and generally consistent with comfort conditions only for cool light. To the contrary, PMV values were slightly negative and consistent with comfort levels typical of category C [18]. This is because PMV index does not account neither gender related differences nor other non-tactile stimulations as light. In addition, the standard deviation values of TSV votes were near to one point (ranging from 0.73 to 1.01 depending upon the group) revealing a significant inter-individual difference within the same group of interviewed.



Fig. 5. Results of the subjective investigation with the two light scenes under winter condition (air temperature in the test room settled at 20 °C).

4 Conclusions

In a general context where the attainment of energy saving goals (e.g. as in nZEB) has to be consistent with high indoor environmental quality levels, it is impossible thinking to maximize a single IEQ component (e.g thermal or visual) without considering possible mutual interactions or negative effects on energy costs.

From this perspective studying the mutual interaction of the four aspects of the IEQ is a crucial need to obtain high overall comfort levels, protect the health of occupants and their productivity and avoid unbalanced design solutions resulting in negative effects on IEQ and buildings energy demand.

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 operating on the set-point temperature of HVAC systems increasing warmth (cold) sensation during winter (summer). Based upon preliminary results obtained in a special mechanically conditioned test room provided with whitetuning LED sources we can confirm that, under winter conditions, cooler light (6000 K) induces a shift of the thermal sensation toward cold. The effect seems to be more pronounced in case of women whose percentage under neutral conditions has almost doubled by changing the CCT from 3000 (warm light) to 6000 K (cool light).

The results of this preliminary investigation will be integrated with the analysis of the answers given on the evaluation and preference scales. This is specially to verify whether the reduction of the thermal sensation votes induced by coo light is associated with higher preferred temperatures and different experienced comfort conditions. Further investigations will be also addressed to verify possible effects of lighting parameters (e.g. illuminance and/or CCT) under different microclimatic conditions (e.g. near thermal neutrality or cold discomfort also accounting for local thermal discomfort). Additional studies will be carried out on a wider and heterogeneous sample of interviewed also considering other human factors (e.g. psychological issues, stress, anxiety). 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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