Influence of lighting colour temperature on indoor thermal perception: A strategy to save energy from the HVAC installations

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ABSTRACT

This paper examines how the lighting colour temperature affects indoor thermal comfort. A test room with three separate environments was set and, in each one of them, a lamp with a different colour temperature was positioned to evaluate the influence of a cold, neutral and warm light. The colour temperatures of the used lamps were 11,530 K, 4,000 K and 1,772 K respectively. During each test, while complying with the EN 12464-1, a lighting level of 500 lx and a uniformity coefficient higher than or equal to 0.7 were maintained. With an air temperature of about 22 °C, 42 people were interviewed and filled a questionnaire structured according to the ISO 10551 to judge the resulting thermal comfort. The study reported a certain influence of the lighting colour temperature on people's thermal perception which was only lower than the one related to the gender. With respect to the ASHRAE 7-point scale, being exposed to the different types of light led to a decrease (0.44 units under cold light) in the mean value of the votes given by the interviewees to judge their thermal perception. Such condition gives the possibility to increase, without varying the thermal perception of the subjects, the air temperature of 1.25 °C, 0.46 °C and 0.23 °C with cold, neutral and warm light respectively. Finally a cross tabulation analysis was performed to compare the votes of the participants before and after they were exposed to the different lights with those predicted by the Predicted Mean Vote (PMV).

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1. Introduction

Two of the most important installations in buildings are related to thermal and lighting issues. Independently from their influence on building users performance, their impact in financial, energetic, environmental and even social terms should also be taken into consideration.

From this point of view, energy efficiency in buildings continues to improve, thanks to policy action and technological advances [1]. Efficiency improvements of 10–20% are possible in most countries through the use of appliances, equipment and lighting products that are already commercially available [2]. In particular, the impact of lighting on the energy consumption in buildings and infrastructures is expected to decrease due to a widespread use of sunlight in indoor lighting [3–6] and, mainly, to the progressive replacement of traditional lighting fixtures with LED lights [7–14].

This means that the impact of HVAC installations on buildings energy consumptions will increase even more.

Although a wrong interpretation of these forecasts might lead to think that the importance of lighting in sustainability, energy consumption and total costs will decrease in the next years, the reality is rather different. Indeed, the massive implementation of LED sources in buildings will take users and designers to a different scenario where the impact of LED lighting on non-visual paths, mainly melatonin suppression and cortisol release [15,16], must be smartly used.

Hence, there are active lines of research trying to exploit the non-visual effects of light [17–19]. Some examples are the proposals to use dynamic LED lighting to prevent the violence among spectators in sport events [20] or the evidences of better recovery and integration of violence victims when performing their tasks under natural light [21].

Given the vast variety of effects caused by the illumination which have not been fully understood yet, one question might be whether it is possible to decrease energy consumptions and environmental impact of climate installations in buildings through lighting. Different studies [22–27] were carried out to evaluate the

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Nomenclature

BF	body fat [kg]
BMI	Body Mass Index [kg/m^2]
D	diameter of the globethermometer [mm]
FFM	fat-free body mass [kg]
H	height [m]
L	illuminance level [lux]
M	metabolic rate [W/m^2]
M_1	metabolic rate corresponding to the activity performed during the survey [W/m^2]
M_2	metabolic rate corresponding to the activity performed 30 min before the survey [W/m^2]
M_{AV}	weighted average of the metabolic rates of the interviewee during the survey and 30 min before [W/m^2]
M_B	basal metabolic rate [W/m^2]
MRT	mean radiant temperature [°C]
PMV	Predicted Mean Vote [-]
PMV$_0$	value of the Predicted Mean Vote in a condition close to the neutral one [-]
Q	radiation budget [W/m^2]
Q_H	turbulent heat flux of sensible heat [W/m^2]
Q_L	latent heat flux [W/m^2]
Q_{RE}	respiratory heat flux (sensible and latent) [W/m^2]
Q_{SW}	latent heat flux from sweat evaporation [W/m^2]
RH	relative humidity [%]
S	storage heat flow for heating or cooling the body mass [W/m^2]
T_A	air temperature [°C]
T_G	globe temperature [°C]
W	weight [kg]
W_P	physical work output [W/m^2]
WS	air velocity [m/s]
ε	emissivity of the globethermometer [-]
δPMV/δT_A	variation in the Predicted Mean Vote due to a unit variation of the air temperature [-]
δPMV/δMRT	variation in the Predicted Mean Vote due to a unit variation of the mean radiant temperature [-]
δPMV/δRH	variation in the Predicted Mean Vote due to a unit variation of the relative humidity [-]
ΔT_A	air temperature variation [°C]
ΔMRT	mean radiant temperature variation [°C]
ΔRH	relative humidity variation [%]

kept at a temperature of 42 °C, which one was the warmest. Each cylinder was characterized by a different colour and green and blue cylinders were considered to be the warmer than red and purple cylinders. Kuno et al. [31] analyzed the influence of the colour of carpets and curtains. They found that a red interior leads to a warmer thermal perception with an increasing temperature and to a cooler thermal perception with a decreasing temperature. Further studies examined the influence of the walls' colour on thermal comfort [26,32–34]. Itten [33] and Clark [32] stressed how the interviewees reported a colder thermal perception in blue/blue-green rooms. However, other cases did not reveal an influence of the colour of walls or rooms. Indeed Greene and Bell [26] and Pedersen [34] asked the interviewees to estimate the temperature of the test rooms in different configurations without reporting significant results.

Houghten et al. [22] studied the thermal perception and the skin and oral temperature of two subjects who stared for 7 h at a screen with a red, blue or white light. The results did not reveal discrepancies in terms of thermal comfort but it should be said that the variations of the screen luminance were not considered. Moreover, the spectral composition of the light was not defined.

Other researches [23–25,27,35,36] were carried out to examine how the illumination colour affects the thermal perception, and more generally, the thermal comfort. Bennett and Rey [27] tried to modify the thermal perception through coloured glasses, without significant differences though. As the same authors explained, this might be caused by the "washed-out" impression related to the glasses. Berry et al. [23] used fluorescent lamps and coloured filters to provide a room with five different types of lighting. In each scenario the air temperature was increased and 25 subjects were asked to claim when they started to feel "uncomfortably warm". However not even this study reported significant variations concerning the thermal perception of the interviewees. Different results were obtained by Fanger et al. [24]. They examined the thermal perception in a room with blue or red light and quantified the difference in 0.4 °C. The hue-heat hypothesis was also confirmed by Albers et al. [25]. They carried out an experiment under realistic conditions in an aircraft cabin and reported that the evaluation of the thermal comfort, on a scale ranging from 1 (very cold) to 7 (hot), is 3.31 with yellow light and 3.19 with blue light. Moreover, they discovered that, if an environment presents yellow lights, the air temperature will be perceived as 0.2 °C higher. Winzen et al. [36] revealed similar results: while referring to the same test environment set by Albers et al. [25], they examined the influence of the colour of the light source finding how a yellow light leads to perceive a warmer air temperature than a blue light. To be more specific, with a scale ranging from 1 (very cold) to 7 (very warm), they reported an average thermal perception of 5.47 with yellow light and 2.57 with blue light. Then Candas and Dufour [35] discovered a tendency to prefer a specific light (e.g., bluish) to compensate for the effects provoked by the temperature (e.g., warm). In a slightly warm environment, they reported an increase in the thermal comfort of 6 units (with a scale ranging from 0 to 100) lighting the environment with a colour temperature of 5000 K rather than 2700 K. Similar results were obtained by Nakamura and Oki [37], who agreed with the tendency to prefer a higher colour temperature in warm environments and vice versa.

In addition, the use of a light with a high colour temperature determines a decrease in the core body temperature. Morita and Tokura [38] and Cajochen [39] estimated this decrease in 0.2 °C whereas Yasukouchi et al. [40] and Shi [41] in 0.1 °C. In the last two studies the effects deriving from a colour temperature of 3000 K were compared to those provoked by a colour temperature of 5000 K and 7500 K [40] and 6000 K [41] respectively.

Taking into account these considerations, the present study examines the possibility to affect the thermal perception through the
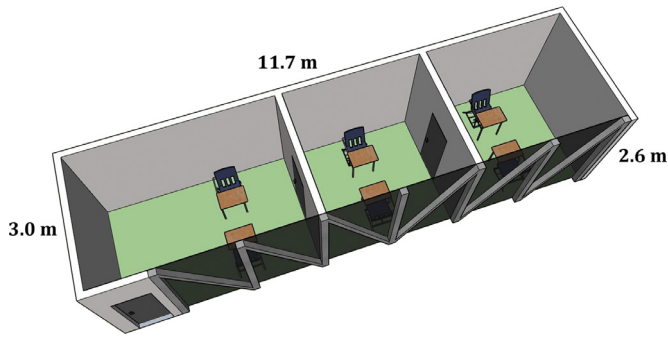
influence of the colour temperature on people's thermal perception, hence, the so called hue-heat hypothesis [28]. The hue-heat hypothesis states that a light or a colour characterized by wave lengths located on the red end of the visual spectrum are perceived as warm, whereas those located on the blue end are perceived as cold. Hence a light with a low colour temperature, being reddish, is perceived as warm whereas one with a high colour temperature, being bluish, is described as cold.

However, it must be specified that those studies that have been carried out until now on the hue-heat hypothesis do not present uniform results. Ho et al. [29] revealed that blue objects or materials are perceived as warmer than other objects. The reason might be that a blue object is thought to be colder than a red one and when the subject realizes that they cause the same thermal sensation, its temperature is overestimated. These findings have been confirmed by Mogensen and English [30]. They performed a study where the subjects were asked to declare, having two cylinders

Fig. 1. Test room of the survey.

colour temperature of the light source. This could enable a smart synergy between the thermal and lighting installations in order to reduce the energy consumptions and emissions of greenhouse gases. For example, the indoor air temperature might be lower in presence of a light source with a low colour temperature during the heating season and vice versa over the cooling season, with resulting energy savings. Hence a field survey was carried out in a test room and thermal perception and preference, personal tolerance and acceptance and the suitability level while performing a certain task were examined in presence of a warm, neutral and cold light. The influence of the different types of light on thermal comfort was also examined through the Friedman test and the Wilcoxon Signed-Rank test. The Friedman test evaluates if there are differences among the thermal perception votes provided by the subjects after they had been exposed to the different types of light. The Wilcoxon Signed-Rank test identifies under which colour temperatures the aforementioned differences occur.

Moreover, the influence of the colour temperature is quantified through the partial F test and the t statistic and it is numerically compared to the one of variables as gender, Body Mass Index (BMI), age and metabolic rate. Then a cross-tabulation analysis was performed where the thermal perception votes given by the interviewees exposed to the different types of lights were compared to those given by the interviewees before the test and those provided by the Predicted Mean Vote (PMV). Finally, the PMV equation was rearranged in terms of partial derivatives. Such procedure gave the possibility to quantify the air temperature variation which is possible to set without modifying the thermal perception of the subjects under the different types of examined light.

2. Materials and methods

2.1. Experimental set-up

This study was carried out in a test room with a length of 11.7 m, a width of 3.0 m and a height of 2.6 m (Fig. 1).

The colour of the ceiling is light grey whereas the floor is dark green with a surface reflectance of 60% and 48% respectively. For what concerns the vertical walls, three of them are white with a reflectance of 80%. The fourth one is made of glass and allows the researchers to supervise the experiment without affecting, with the heat generated by their bodies, the thermal perception of the participants. It is important to keep in mind that a person standing generates about 70 W per m^2 of skin surface [42]. The test room is divided into three different separate spaces. In each space a specific type of LED lamp was placed at a height of 2.40 m to expose the subjects to scenarios with a warm, neutral and cold light. The colour temperatures of the different lights were 1772 K, 4000 K and 11,530 K respectively and LED lamps were chosen due to the small amount of produced heat, thus avoiding increases in participant's body temperature deriving from the infrared radiation. Every space

presented two chairs with a folding desk similar to those characterizing a class-room facility, which is the environment where the participants usually spend more hours every day. In addition, the furniture and general environment were quite comfortable and familiar. This approach was chosen to minimize the potential bias concerning the test environment. Moreover, taking as a point of reference the desk, the illuminance level was constantly measured thanks to a lux meter to be sure it complied with the regulations. From this point of view the EN 12464-1 [43] expects an average illuminance level of 500 lx and a uniformity coefficient higher than or equal to 0.7. These values were respected and with reference to the average illuminance level the values of 504.6 lx (warm light), 510.2 lx (neutral light) and 518.5 lx (cold light) were measured. Even though there were discrepancies among the aforementioned values, their effect on thermal perception was not significant [44]. Moreover, during each test different measurements on the writing desk were performed to ensure that the uniformity coefficient was also satisfied. In order to monitor the values of the environmental variables in the test room, 4 probes connected to a microclimate control unit were used:

- a PT 100 platinum thermoresistance to measure the air temperature;
- a globethermometer with a diameter of 150 mm and characterized by a black copper globe with a reflection coefficient lower than 2% to measure the globe temperature;
- a forced ventilation psychrometer with a tank of distilled water to measure relative humidity;
- a hot wire anemometer to measure the air velocity.

Having the possibility to modify the height of the control unit, the probes were placed at 0.6 m. This allowed to measure the values of the environmental variables at the height of the centre of gravity in the human body for those sitting down as the subjects interviewed.

Table 1 reports the metrological properties of the used instruments.

In order to calculate the mean radiant temperature values Eq. (1) [45] was used:

$$MRT = \left[(T_G + 273.15)^4 + (T_G - T_A) \cdot \left(1.1 \cdot 10^8 \cdot WS^{0.6} \right) / \left(\varepsilon \cdot D^{0.4} \right) \right]^{0.25} \tag{1}$$

where ε and D are the emissivity and the diameter of the globethermometer respectively.

2.2. Participants

The sample was formed by 42 unpaid volunteers (Table 2).

The age of the participants was between 33 and 19 with an average value of 23 (standard deviation = 2.54). Concerning the gender, 24 were men whereas 18 were women.

Their colour perception was preliminarily assessed through the Ishihara pseudo-isochromatic plates and all of them were eligible.

Then the metabolic rate M of each subject was determined through Eq. (2):

$$M = M_{AV} + M_B \tag{2}$$

M_{AV}, according to Bouden and Ghrab [46], is obtained through a weighted average of the metabolic rates of the interviewee during the survey (M_1) and 30 min before (M_2). Therefore, the calculation of M_{AV} was based on Eq. (3):

$$M_{AV} = 0.7 \cdot M_1 + 0.3 \cdot M_2 \tag{3}$$

Being the subjects sitting down during the survey, M_1 will be 58 W/m^2.

Table 1
Metrological properties of the used instruments to measure the environmental variables.

Probe	Measured variable	Measured range	Resolution	Accuracy
PT 100 platinum thermoresistance	T_A [°C]	(-50)–$(+80)$	0.01	± 0.5 °C above -7 °C
Hot wire anemometer	WS [m s^{-1}]	(0)–(45)	0.01	± 1 m/s
Forced ventilation psychometer	RH [%]	(0)–(100)	0.1	$\pm 3\%$ (0–90%), $\pm 4\%$ (90–100%)
Globethermometer	T_G [°C]	(-40)–(80)	0.01	≤ 0.1 °C at 0 °C DIN 43,760 1/3
Lux meter	L [lux]	(0.01)–$(299,900)$	0.001	$\pm 2\%$

Table 2
Data related to the examined sample.

	Age	Weight	Height	Body mass index	Metabolic rate
Maximum	33.00	120.00	1.92	40.09	115.00
Minimum	19.00	49.00	1.58	18.83	60.00
Mean	23.25	67.80	1.71	22.90	73.73
Mode	22.50	72.00	1.70	24.91	60.00
Median	22.50	64.00	1.70	22.55	60.00
Std. deviation	2.54	14.45	0.08	3.76	21.87
25th percentile	22.50	57.50	1.65	20.29	60.00
75th percentile	22.50	77.50	1.76	24.91	70.00
Skewness	2.35	1.35	0.17	2.69	1.33
Kurtosis	6.13	3.01	-0.61	10.80	-0.07

On the other hand M_B (Eq. (2)) is the basal metabolic rate and it is calculated through Eq. (4) [47]:

$$M_B = 0.0484 \cdot (19.7 \cdot \text{FFM} + 743) \tag{4}$$

where FFM is the fat-free body mass, assessed through Eq. (5):

$$\text{FFM} = W - \text{BF} \tag{5}$$

In Eq. (5) W is the body weight in kg and BF is the body fat, calculated for women and men through Eqs. (6) and (7) respectively [48]:

$$\text{BF} = 0.737 \cdot W - 5.15 \cdot H^3 + 0.37 \tag{6}$$

$$\text{BF} = 0.685 \cdot W - 5.86 \cdot H^3 + 0.42 \tag{7}$$

In Eqs. (6–7) H is the height in m and, together with W, determines the Body Mass Index (BMI) (Eq. (8)) [49]:

$$\text{BMI} = W/H^2 \tag{8}$$

and the skin surface of each subject (Eq. (9)) [42]:

$$\text{Dubois area} = 0.202 \cdot \left(W^{0.425} \cdot H^{0.725} \right) \tag{9}$$

The value of the skin surface is important because the Predicted Mean Vote (PMV), whose predicted values are compared to the thermal perception votes given by the interviewees, was determined through the software Rayman [50]. This software requires the metabolic rate M in Watt as input parameter. Hence the resulting value in W/m^2 obtained through Eq. (2) was multiplied by the skin surface of the corresponding interviewee.

Each participant was asked to wear standard clothes for the survey: trousers and short-sleeve shirt. Women were allowed to wear knee-length skirt and short-sleeve shirt. This was due to the importance of having thermal clothing insulation values as much similar as possible: indeed, the first ensemble reports a thermal clothing insulation of 0.57 clo whereas the second 0.54 clo (1 clo = 0.155 m^2 K W^{-1}). The insulation of the chair in the experiment was also evaluated. According to Table B3 of the standard ASHRAE 55 [42], the used chair could be considered a wooden side arm chair, which is the one used in most of the basic studies of thermal comfort that were carried out to establish the PMV-PPD index. However, in the case of this chair and with clothing ensembles with standing insulation values between 0.5 and 1.2 clo, the aforementioned standard does not report additional insulation.

2.3. Questionnaire

The questionnaire used in this study was structured according to the ISO 10551 [51] with a clear and simple language (Fig. 2).

It was formed by 3 sections. The first part was about personal information: gender, age, weight, height and activity performed 30 min before the test. The second part of the questionnaire, which the interviewee was asked to fill before being exposed to a light with a specific colour temperature, concerned thermal perception, thermal preference, personal acceptability and personal tolerance. According to ISO 7730 [52], ASHRAE Standard 55-2004 [42] and Huebner et al. [44], the thermal perception is evaluated through the so called ASHRAE 7-point scale (cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm $(+1)$, warm $(+2)$ and hot $(+3)$). On the other hand, the McIntyre scale (cooler (-1), no change (0) and warmer $(+1)$) and a 5-point scale ranging from perfectly bearable (1) to unbearable (5) were used for thermal preference and personal tolerance respectively. The third part of the questionnaire was like the second section with the only difference that it included a question aimed at evaluating the suitability level of the task while performing the test. The subjects filled this third part after they had been exposed for 30 min to a specific type of light and this allowed to determine the way the light and its colour temperature affected thermal comfort.

The questionnaire here described was answered by the interviewee during the first of three tests part of the experiment. In the other two, the subjects filled up the second and third section (skipping the part concerning personal information). The questionnaire was in Spanish, which is the mother tongue of the participants. Finally, every questionnaire was related to the corresponding interviewee and to the measured environmental variables through an ID.

2.4. Experimental procedure

At the beginning of the survey the clothing ensembles of the participants were checked in order to be sure they complied with those suggested by the researchers. If a discrepancy was revealed, the subject was asked to take off or put on single garments.

The interviewees signed approving the form and the researchers presented the experiment as a study to evaluate the influence of different environmental conditions on thermal comfort.

THERMAL COMFORT QUESTIONNAIRE

This questionnaire is entirely voluntary. If you do not wish to complete it, or any part of it, you are under no obligation to do so.

Date: ..... / ..... /	Time: ..... :	Questionnaire n°: .....

	BEFORE THE TASK
1	**Gender:** □ male □ female
2	**Age:** ....
3	**Weight:** .... kg
4	**Height:** .... m
5	**For the last half hour have you been mainly:** □ sleeping □ sitting □ standing □ walking □ doing sports □ other (please specify): ....
6	**How are you feeling in this moment?** □ cold □ cool □ slightly cool □ neutral □ slightly warm □ warm □ hot
7	**How would you prefer to feel?** □ cooler □ no change □ warmer
8	**Taking into account your personal preference only, would you rather accept than reject this climatic environment?** □ yes □ no
9	**Is this environment, in your opinion. . .?** □ Perfectly bearable □ Slightly difficult to bear □ Fairly difficult to bear □ Very difficult to bear □ Unbearable
	AFTER THE TASK
10	**How are you feeling in this moment?** □ cold □ cool □ slightly cool □ neutral □ slightly warm □ warm □ hot
11	**How would you prefer to feel?** □ cooler □ no change □ warmer
12	**Taking into account your personal preference only, would you rather accept than reject this climatic environment?** □ yes □ no
13	**Is this environment, in your opinion. . .?** □ Perfectly bearable □ Slightly difficult to bear □ Fairly difficult to bear □ Very difficult to bear □ Unbearable
14	**How do you judge the suitability level of the task while performing the test?** □ Very comfortable □ Comfortable □ Neutral □ Slightly uncomfortable □ Very uncomfortable

Fig. 2. Questionnaire used in the survey.

According to Huebner et al. [44], specific conditions were not mentioned in order to avoid possible bias.

Before starting the experiment, the interviewees were subject to a preparatory time interval of 15 min in a space right outside the test room and characterized by a certain uniformity in terms of lighting conditions and temperature. This allowed the interviewees to have a similar pre-experimental metabolic rate and a certain acclimatization time [44]. The Ishihara test was also performed to evaluate their colour perception.

The next step was to let one couple of participants at a time to enter the test room (except for two episodes where the subject performed the test alone) and the different sessions of the experiment were carried out with a temperature around 22 °C (mean value = 21.9 °C, sum of the deviations' squares = 0.3 °C).

The temperature in the test room was almost constant thanks to its location. Indeed the test room where the experiment was carried out is located on the third floor below the ground level of the Faculty of Civil Engineering of the University of Granada. This choice is due to the excellent thermal inertia of the aforementioned room, which had been checked many times in different seasons through the years and, in order to have an air temperature as much constant as possible, the survey was carried out during consecutive days. In addition, the underground location of the test room did not allow the natural light to enter, thus avoiding any combination with the tested artificial light.

Fig. 3. Participant during the survey while filling the questionnaire.

The participants were asked to sit down on a chair with a folding desk and adopt the most comfortable reading position for 30 min. The reading was chosen by the participants and supervised by the researchers. The only constrains were the topic (not stressful topics) and the format (always paper, never tablets, e-books or any light emitting device).

Before starting the experiment, once comfortably sat, the participants answered the first and second part of the questionnaire (Fig. 3).

Then, they read for 30 min under one of the three types of light (warm, neutral or cold) and filled up the third section of the survey. Subsequently they were exposed for 10 min to a neutral light to neutralize their colour impressions, followed by 30 min with one of the other two lights. Also in this case the sample was asked to fill the second and third section of the questionnaire. Finally, the process was repeated for the third type of light. The exposure order of the participants was balanced.

2.5. Predicted mean vote (PMV)

The votes provided by the interviewees to judge their thermal perception were compared to those calculated through the Predicted Mean Vote (PMV) [53]. This index was also used to examine the possible indoor air temperature variation which is possible to set under the three different types of light without altering the occupants thermal perception. The PMV predicts the mean value of the votes that a large group of people would give to judge the thermohygrometric conditions of a specific environment and its use is recommended by ISO 7730 [52] and ASHRAE 55 [42]. It was initially developed to be used in indoor environments through a field survey based on a sample of 1565 people.

Then Jendritzky and Nubler [54] parametrized the radiative fluxes to take into account the shortwave radiation and, with the name of "Klima-Michel Model" (KMM), it was possible to use the PMV outdoors as well. The PMV model is function of four environmental variables (air temperature, mean radiant temperature, wind speed and relative humidity) and two operative variables (metabolic rate and thermal clothing insulation) and it is defined according to Eq. (10):

$$PMV = \left(0.303 \cdot e^{-0.036M} + 0.028\right) \cdot S \tag{10}$$

where M is the metabolic rate and S is the storage related to the energy budget of the human body. Hence S is (Eq. (11)):

$$\begin{aligned} M + W_P + Q\,(\text{MRT, WS}) + Q_H\,(T_A, \text{WS}) + Q_L\,(\text{RH, WS}) \\ + Q_{SW}\,(\text{RH, WS}) + Q_{RE}\,(T_A, \text{RH}) = S \end{aligned} \tag{11}$$

All the terms reported in Eq. (11) are positive if they represent an energy gain for the human body. This is why the metabolic rate M is always positive, whereas the physical work output W, the latent heat flow related to the evaporation of moisture diffused through the skin Q_L and the latent heat flow from sweat evaporation Q_{SW} are always negative.

Finally, the PMV depends on the ASHRAE 7-point scale, which ranges from -3 (cold) to $+3$ (hot) where 0 corresponds to the thermal neutral condition. Such scale was also used by the participants in the survey to evaluate their thermal perception.

3. Results and discussion

Table 3 reports the results of the survey.

While referring to the thermal perception of the interviewees after the tests, it is possible to notice a discrepancy of about 0.50 units between the scenarios with cold and warm lights. This condition leads to state that there is a certain influence of the type of light on thermal perception. However it is important to point out that the mean values of the votes given by the interviewees were always part of that range that ISO 7730 [52] identifies as thermal comfort $((-1)\text{-}(1))$. The influence of the colour temperature is then confirmed through the thermal preference of the subjects. If the obtained mean values under neutral and warm lights are close to the option "no change", the situation is completely different for the votes given under cold light. Indeed, the mean value is 2.41 and there is a general need of warmer thermal conditions. It must be specified that both for thermal preference and perception, the values concerning the neutral light are in an intermediate position and tend to the values corresponding to the colour temperature of 1772 K. The situation is different if the personal acceptability and the suitability of the task during the test are taken into consideration. The best results continue to be those registered in presence of neutral light but, differently from what happened in the other cases, they are followed by those obtained under cold light. Finally, small differences were found in terms of personal tolerance between cold and warm lights.

The influence of lighting colour temperature on thermal comfort is also supported by statistical analysis.

In this study the Friedman test reported the values of 3.694 and 0.158 for χ^2 and p respectively. These values are slightly higher than what Baniya et al. [55] found with an air temperature of 20 °C. Indeed, these researchers had compared the effect of the colour temperatures of 2700 K, 4000 K and 6200 K reporting the values of $\chi^2 = 3.033$ and $p = 0.219$. The same authors [55] repeated the experiment with an air temperature of 25 °C but in this last scenario the influence of the colour temperature ($\chi^2 = 8.456$, $p = 0.015$) was higher than what reported in the present study.

Then an analysis based on the Wilcoxon Signed-Rank test was carried out. It revealed how the main differences in terms of thermal comfort occur between the thermal perception of the sub-

Table 3

Results of the answers provided by the interviewees related to thermal perception and preference, personal tolerance and acceptance and suitability level while performing the task.

Thermal perception (Cold (−3), Cool (−2), Slightly cool (−1), Neutral (0), Slightly warm (+1), Warm (+2), Hot (+3))						
	1772 K		4000 K		11,530 K	
	Before the task	After the task	Before the task	After the task	Before the task	After the task
Mean Value	0.00	−0.08	−0.06	−0.22	−0.15	−0.59
Standard deviation	0.96	1.03	0.85	0.63	0.89	0.73
25th percentile	0.00	−1.00	−1.00	−1.00	−0.50	−1.00
75th percentile	0.00	1.00	0.00	0.00	0.00	0.00

Thermal preference (Cooler (1), No change (2) Warmer (3))						
	1772 K		4000 K		11,530 K	
	Before the task	After the task	Before the task	After the task	Before the task	After the task
Mean value	2.04	2.04	1.78	1.94	2.12	2.41
Standard deviation	0.52	0.65	0.53	0.52	0.51	0.49
25th percentile	2.00	2.00	1.25	2.00	2.00	2.00
75th percentile	2.00	2.00	2.00	2.00	2.00	3.00

Suitability of the task (Very comfortable (1), Comfortable (2), Neutral (3), Slightly uncomfortable (4), Very uncomfortable (5))			
	1772 K	4000 K	11,530 K
Mean value	2.44	1.72	2.12
Standard deviation	0.89	0.65	0.76
25th percentile	2.00	1.00	2.00
75th percentile	3.00	2.00	3.00

Personal acceptability						
	1772 K		4000 K		11,530 K	
	Before the task	After the task	Before the task	After the task	Before the task	After the task
Accept	81.5%	59.3%	94.5%	83.4%	88.9%	66.7%
Reject	18.5%	40.7%	5.5%	16.6%	11.1%	33.3%

Personal tolerance (Perfectly bearable (1), Slightly difficult to bear (2), Fairly difficult to bear (3), Very difficult to bear (4), Unbearable (5))						
	1772 K		4000 K		11,530 K	
	Before the task	After the task	Before the task	After the task	Before the task	After the task
Mean Value	1.35	1.42	1.28	1.22	1.26	1.48
Standard deviation	0.55	0.57	0.45	0.42	0.58	0.63
25th percentile	1.00	1.00	1.00	1.00	1.00	1.00
75th percentile	2.00	2.00	1.75	1.00	1.00	2.00

jects under neutral and cold light ($Z = −2.066$, $p = 0.039$). Significant variations also characterized the comparison between warm and cold light ($Z = −1.758$, $p = 0.079$), whereas not so important were the results provided by the comparison of warm and neutral light ($Z = −0.372$, $p = 0.710$). In this last case the results are affected by the small difference of the mean values representing the thermal perception and by the standard deviation reported for the test under warm light. Indeed, the aforementioned standard deviation value is higher than the one determined in the other two tests and leads to a certain dispersion of the data (which sometimes overlap with those of the neutral light). These results prove in part what Baniya et al. [55] stated. Referring to a temperature of 25 °C, they discovered higher discrepancies ($Z = −3.338$, $p < 0.001$) for what concerns the thermal comfort between warm (2700 K) and neutral light (4000 K). On the other hand, lower values concerned the comparison between the colour temperatures of 2700 K and 6200 K ($Z = −1.436$, $p = 0.151$) and of 4000 K and 6200 K ($Z = −1.320$, $p = 0.187$).

According to Yasukouchi et al. [40], it should be also considered that the influence of the colour temperature on thermal perception and comfort might increase with lower air temperatures. However, the present study refers to indoor environments destined to be workplaces, hence the air temperature can't be too low. Another factor that might have affected the thermal perception votes given by the interviewees is the time interval they had been exposed to a certain type of light. Indeed, in this study the subjects filled the questionnaire after 30 min. Such period of time can con-

tribute to the chromatic adaptation and bring the interviewees to perceive the light as white rather than reddish or bluish [55]. Then the influence related to the suitability of the task during the test must be considered. Some researchers stressed the fact that the interviewees usually give the best votes, in terms of thermal perception, when they are exposed to their favourite colour temperature [55]. This is why during this survey the best votes were registered in presence of the neutral colour temperature, both for the thermal perception and the suitability of the task during the test. Indeed, a neutral colour temperature usually characterizes the light to which these subjects are exposed to and this is a further factor that might have affected the results.

Even more interesting considerations concern the influence of some variables on participants' thermal perception after being exposed to the different types of light. In order to examine this issue the partial *F* test was implemented: this test allows to evaluate in a quantitative way the contribution that each independent variable is able to provide to a possible developed model. Therefore, it gives the possibility to estimate how much each variable might affect the dependent variable (as already said the thermal perception after each test). In this study, a variable can improve a hypothetical developed model if the value of the partial *F* test is higher than 2.51, the critical value assessed through the evaluation of the 95th percentile of Fischer's pdf.

As showed in Fig. 4, the highest value (5.47) is obtained for the gender. This finds a confirmation in the results of the study carried out by Liu et al. [56]. Indeed they examined the different
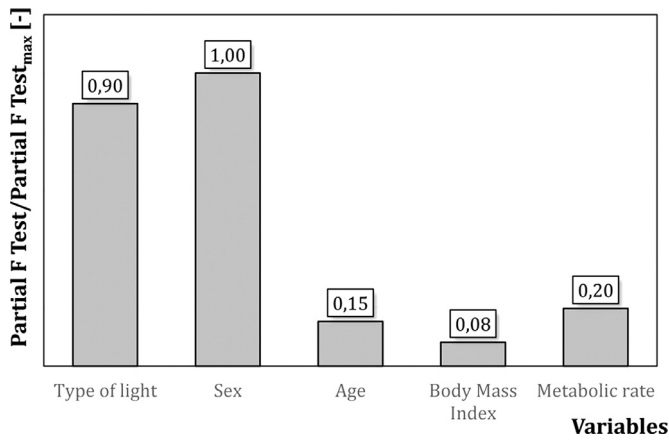
Fig. 4. Partial *F* test values normalized with respect to the maximum revealed value.

Table 4
Values of the *t* statistic for the examined independent variables.

t Statistic Type of light	Gender	Age	Body mass index	Metabolic rate
2.10	−2.34	−0.36	−0.19	−0.46

physiological feedbacks of subjects exposed to the same thermal environment with respect to 12 different clothing ensembles. The experiment was performed for four different values of the air temperature (10, 16, 22 and 28 °C) and stressed how the thermal sensitiveness in women is higher than the one characterizing men. The existence of significant differences in the thermal perception and preference of male and female subjects was also proved by Kuntz Maykot et al. [57] based on 83 field studies in three office buildings located in Florianopolis, southern Brazil. From a more general point of view, Van Craenendonck et al. [58] highlighted how the hypothesis of gender differences in thermal perception is examined in 30 papers and how 21 of them confirm it.

With respect to the present study and the partial *F* test, it is also important to stress that the second value (4.39) is reported by the type of light. This is showed through Fig. 4 reporting the values of the partial *F* test normalized with respect to the highest revealed value.

Moreover, it is possible to notice how variables as the metabolic rate, age and the Body Mass Index (BMI) affect less the thermal perception of the subjects after the test. This is proved by the evaluation of the values determined for the t statistic (Table 4).

This test [59,60] allows to establish whether there is a significant relation between the examined independent variables and the thermal perception after the exposure to the different lights. This happens if the value of the t statistic exceeds the range ±2.04, obtained through the percentile $(1-\alpha)\%$ concerning the Student's pdf with a significance level of 0.05 and 75 degrees of freedom.

Once the influence of the colour temperature of lighting on the subjects' thermal perception is confirmed, the possible variation in the air temperature has to be assessed.

This is why the relation of the Predicted Mean Vote (PMV) is rearranged as follows (Eq. (12)):

$$PMV = PMV_0 + \frac{\delta PMV}{\delta T_A} \cdot \Delta T_A + \frac{\delta PMV}{\delta MRT} \cdot \Delta MRT + \frac{\delta PMV}{\delta RH} \cdot \Delta RH$$

(12)

where:

- PMV_0 is the value of the Predicted Mean Vote in a condition close to the neutral one (PMV = 0);

- ΔT_A, ΔMRT and ΔRH are the variations in the air temperature, mean radiant temperature and relative humidity respectively;
- $\delta PMV/\delta T_A$, $\delta PMV/\delta MRT$ and $\delta PMV/\delta RH$ refer to the variations in the Predicted Mean Vote due to a unit variation of the air temperature, mean radiant temperature and relative humidity respectively.

If the scenario with cold light is taken as an example, in Eq. (12) the PMV_0 and PMV are set to −0.15 and −0.59 and they represent, with respect to the ASHRAE 7-point scale, the mean values of the votes provided by the interviewees before and after the test. ΔMRT and ΔRH are then set to 0 whereas $\delta PMV/\delta T_A$, obtained based on Fig. 5 [53], is set to 0.35. The value of the thermal clothing insulation (0.55 clo) represents the mean value deriving from the clothing ensembles of the interviewed subjects and it is chosen according to the standard ASHRAE 55-2004 [42]. The chart corresponding to the metabolic rate per unit of skin surface $M/A_{DU} = 50$ kcal h^{-1} m^{-2} (Fig. 5) is then used. Indeed 50 kcal h^{-1} m^{-2} is the closest value to the mean metabolic rate obtained based on those calculated for the participants to the survey among those categorized by Fanger (50 kcal h^{-1} m^{-2}, 100 kcal h^{-1} m^{-2} and 150 kcal h^{-1} m^{-2}) [53].

By substituting the values previously reported in Eq. (12), the result is $|\Delta T_A| = 1.25$ °C. With cold light, it represents the increase in the air temperature that might be set without provoking a variation in people's thermal perception. On the other hand, with warm and neutral light such increase can be of 0.23 °C and 0.46 °C respectively.

These considerations can be confirmed through Fig. 6. It shows how the thermal perception of the participants changes after being exposed to the different types of light (hence colour temperatures) through an analysis based on the number of occurrences related to each thermal perception vote. This is why the votes given by the participants after being exposed to the different types of light were related to those provided before the test.

For example with cold light it can be noticed how the aforementioned increase in the air temperature is possible because of the high number of interviewees that, after the test, switched from (0) to (−1) their thermal perception vote (26%). It is also important the number of people that, once they expressed a preliminary vote of (+1), assigned to their thermal perception the votes (−1) and (0) (referring to the total number of subjects interviewed, 7.5% and 11% respectively).

On the other hand with neutral light, a significant percentage concerned those who decreased their vote from (0) to (−1)(22%) and from (+1) to (0)(11.1%). However it should be said that the results are mitigated because 22.2% of the interviewed subjects reported an increase in their thermal perception vote from (−1) to (0).

With a colour temperature of 1772 K, the allowed increase in the air temperature is related to the fact that 38.5% of the subjects did not change their perception, thus maintaining a neutral thermal condition.

Further interesting considerations concern Fig. 7, showing the importance of taking into account even lighting aspects during the evaluation of occupants' thermal perception. Indeed Fig. 7 compares the thermal perception votes of the participants after being exposed to the different types of light with those obtained through the Predicted Mean Vote (PMV), the most common index to study the thermohygrometric conditions in indoor environments. It is possible to compare them because the ASHRAE 7-point scale was used in both cases. Moreover, the Predicted Mean Vote (PMV) was developed in indoor environments with neutral light. This is why the major differences occur in the tests performed in presence of cold and warm light.
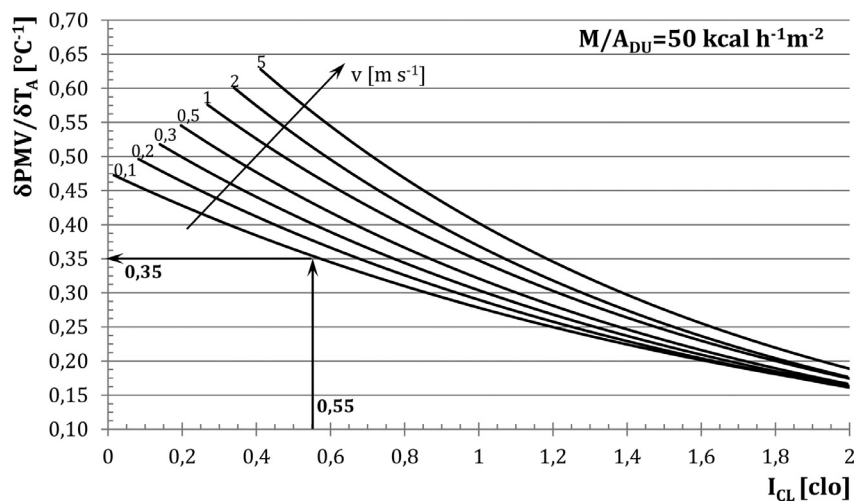
Fig. 5. Chart used to obtain the value of δPMV/δT$_A$ [53].
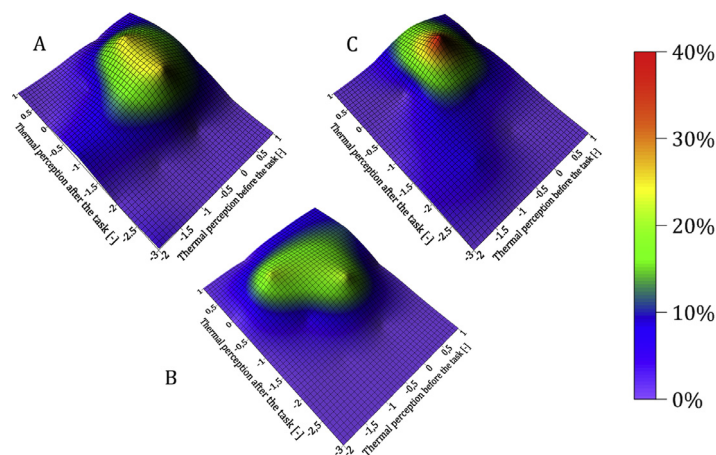

Fig. 6. Comparison among the votes of the interviewees with respect to the thermal perception before and after the exposure to cold (A), neutral (B) and warm (C) light.
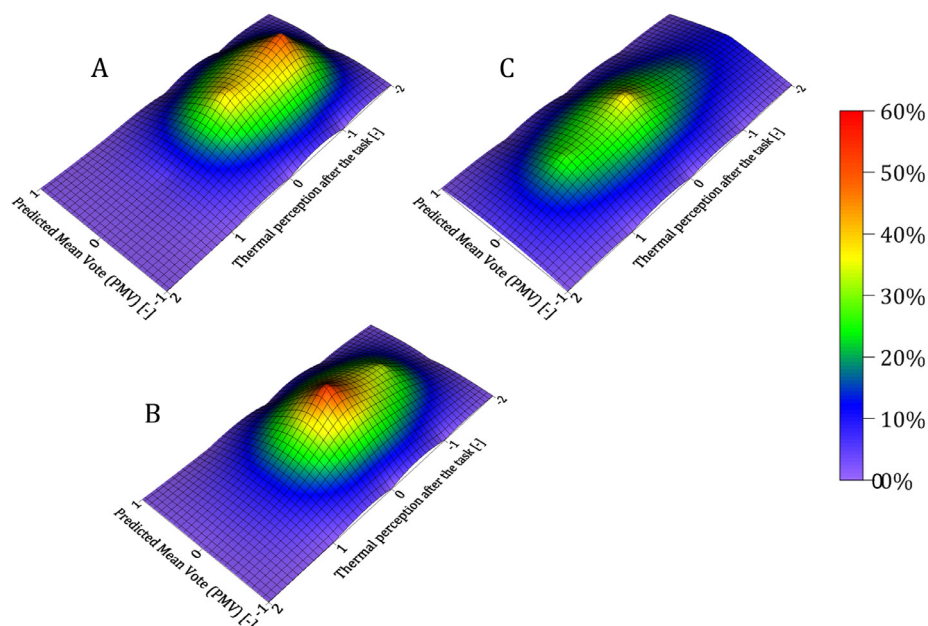

Fig. 7. Comparison between the values deriving from the Predicted Mean Vote (PMV) model and those provided by the interviewees while referring to the environmental conditions after the tests with cold (A), neutral (B) and warm (C) light.

In particular, it is possible to notice how with cold light the correspondence between the values of the Predicted Mean Vote (PMV) and those provided by the interviewed subjects is not significant. In the great majority of the cases (96%) the environmental and operative variables led to a PMV value of (0) and only 40% of the subjects reported an equal corresponding thermal perception vote, thus confirming how important the type of light and its colour temperature are in the field of indoor thermal comfort.

On the other hand a higher predictive ability of the PMV is revealed for a light with a neutral colour temperature. Indeed in 56% of the cases a value equal to (0) both for the PMV and the vote provided by the interviewed subjects is reported.

Finally, the situation is different in presence of warm light. Fig. 7(C) shows a peak of 38% in correspondence of a neutral condition but at the same time a higher variety in the thermal perception votes. With a PMV of (0), a vote of (−2) and (+2) is revealed in 12% and 4% of the cases respectively.

4. Conclusions

This study examines the influence of the type of light and its colour temperature on people's thermal perception. Therefore, a test room with three different separate environments is set. Each environment is characterized by a certain type of light to evaluate the influence of a cold, neutral and warm light (the colour temperatures are 11,530 K, 4000 K and 1772 K respectively). The sample is formed by 42 subjects who were exposed for 30 min to each one of the aforementioned lights and, before every test, the effects of the previous colour temperature were neutralized to let the subject be exposed to the next type of light. The interviewees were then asked to wear standard clothing ensembles and filled a questionnaire structured according to the ISO 10551. Therefore, the interviewees provided personal information and judged their own thermal perception and preference, personal tolerance and acceptability and the suitability of the task during the test. Different environmental variables were also measured during every test and this allowed to relate certain values of air temperature, wind velocity, mean radiant temperature and relative humidity to each subject.

While observing the obtained results, a certain influence of the light and its colour temperature on thermal perception is reported. Indeed, a discrepancy of 0.51 units between the mean values of the votes given by the interviewees after they were exposed to warm and cold lights is revealed.

Such discrepancies are also confirmed by the Friedman's test whereas the Wilcoxon Signed-Rank test allowed to identify those differences mainly among the votes given after the subjects were exposed to cold and neutral lights. The influence of the colour temperature was then quantitatively evaluated through the partial F test and the values obtained for each variable were normalized with respect to the maximum reported value. It is important to notice that the type of light reported the value of 0.90, lower only than that related to the gender (1.00). These results were confirmed through the t statistic. Indeed, the gender and the type of light reported the values of (−2.34) and (2.10) respectively. In order to have energy savings, the variation in the indoor air temperature due to a different thermal perception of the subject deriving from the used type of light was also determined. In the present study, every colour temperature led to a decrease in the mean value of the votes given by the participants in the survey after the test. Hence while rearranging the Predicted Mean Vote (PMV) relation in terms of partial derivatives, it was possible to experience an increase in the air temperature of 1.25 °C, 0.46 °C and 0.23 °C with cold, neutral and warm light respectively. This means that, during summer, the air temperature in a certain environment characterized by a light with a high colour temperature can increase more than one degree without modifying occupants thermal per-

ception. The influence of the type of light on indoor thermal comfort was finally proved by the comparison between the PMV values and those provided by the interviewees after the tests. A possible reason could lie in the fact that the PMV was developed through a survey carried out in environments with a neutral light. This led to a certain similarity with the results of the test carried out under a colour temperature of 4000 K and at the same time to a discrepancy with those provided in presence of warm and cold light. Indeed under the last type of light a thermal perception vote given by the interviewees after the task of −1 corresponds to a PMV equal to 0 in more than half of the scenarios.

Some limitations of the study could be related to the chosen lighting colour temperatures and to the effects deriving from a prolonged exposition to a certain type of light. Moreover, it should be specified that the room is an experimental facility and participants might be psychologically biased by the context to which they are exposed. However future developments in the research will have a narrow range for what concerns the examined lighting colour temperatures and evaluate the relation between the thermal perception and lighting colour temperature even during the cold season. Indeed, from this point of view it is possible that the indoor air temperature might be lower in presence of a warm light during the heating season.

Conflict of interest and authorship conformation

None.

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