Energy Research & Social Science 15 (2016) 45–57

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Saving energy with light? Experimental studies assessing the impact of colour temperature on thermal comfort

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ARTICLE INFO

Article history:
Received 29 September 2015
Received in revised form 19 February 2016
Accepted 22 February 2016

Keywords:
Thermal comfort
Colour temperature
Hue-heat-hypothesis
Energy saving

ABSTRACT

We tested whether the colour temperature of the illumination (realised through manipulating the ceiling light) impacted on thermal comfort, based on the hypothesis that a lower colour temperature is associated with feeling warmer and a higher colour temperature with feeling cooler. If confirmed, then light might be a tool for energy-saving through allowing ambient air temperatures to vary over a wider range and hence reducing the need for space heating and cooling.

Testing took place in a climate chamber. In Study 1, comfort ratings were collected using thermal comfort surveys ($N = 32$). In Study 2, an observational design was used, where changes in clothing level, interpreted as thermal discomfort responses, were observed ($N = 32$). We compared comfort ratings and changes in clothing level under light with a colour temperature of 2700 K vs. 6500 K. Results partly confirmed the hypotheses: both self-report and observation indicated higher comfort under the low colour temperature. Further research will need to replicate findings in a real-world setting to see if light might indeed be a tool to modulate thermal comfort, and hence reduce usage of heating and cooling.

1. Introduction

Reducing energy consumption in residential and non-residential buildings is one of the main challenges faced in moving towards a more sustainable future. Over recent years there have been considerable bodies of research on areas such as retrofit strategies and ‘smart technologies’ (e.g. Refs. [20,19,73]). Extensive research has also been carried out on behaviour change programmes (for a review see Ref. [1]) such as giving occupants feedback on their consumption (e.g. [42,11]), and making energy ‘visible’ [28]. In this paper, we researched a different approach towards reducing energy consumption based on the idea of the ‘hue-heat hypothesis’ [3] which states that a warm (i.e. reddish/yellowish) ambient coloured light is felt as warm, while a ‘cold’ (i.e. bluish) coloured light is felt as (comparatively) cool. Whilst the main focus of this paper is to collect further evidence for the effect of light on thermal perception/comfort, the ultimate goal would be to use manipulation of the ambient light colour as a tool for energy-saving in buildings if temperatures could be lowered under a reddish/yellowish illumination in the heating season, or, conversely, be kept higher under bluish illumination in the cooling season.

As shown in a detailed analysis of papers published in major energy-related journals, there is comparatively little human-centred, social- science research in this field, as is truly multidisciplinary research [66]. Our work adds to this under-researched area by applying psychological theory to a practical energy-related problem using thorough experimental research.

1.1. The hue-heat-hypothesis

Starting point of the hue-heat-hypothesis is the idea of psychological distinction between “warm colours” and “cool colours”. Blue, green and purple colours are considered to be cool, while yellowish and reddish hues are seen as warm [58]. In everyday life, the association between those colours and thermal temperature may be found for example, in the coding for taps, where red symbols refer to warm, blue symbols to cold water.

The distinction between warm and cool colours may be found since the 18th century [26], and was intensively elaborated in Goethe’s colour theory [27]. This divide between warm and cool colours has also been found in colour naming patterns across fun-

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http://dx.doi.org/10.1016/j.erss.2016.02.008

damentally different languages [48], and it has been shown that observers tend to associate certain colours with “warm” and others with “cool” [58]. Finally, the association between colour and temperature is also reflected in the association of colours with warm and cool objects, such as red with fire, and blue with ice [72].

In the following section, we review current evidence on the hue-heat-hypothesis.

We have only looked at those studies that have assessed thermal perception, not studies that look at what colours are characterized as ‘warm’ or ‘cold’. Given the relative paucity of studies on the hue-heat-hypothesis, we reviewed all studies relating colour to thermal perception, not only those manipulating the colour of illumination, as tested in our studies.

When investigating the judgement of thermal temperature and colour of objects and material, effects opposite to the hue-heat-hypothesis have been found, according to which blue objects or materials are perceived to be warmer [32,53]. Ho et al. [32] suggested that it might be that we expect blue objects to feel colder; if they are then of the same temperature as a red object; we assume that in fact, the blue object must be warmer.

Another line of research investigated the effects of wall colours on the judgment of room temperature. Some of those studies have found effects in line with the hue-heat-hypothesis: Itten [41] and Clark [15] found that comfort was significantly impacted by wall colour, with participants feeling colder in blue/blue-green rooms. However, others did not observe any reliable effect of colour of the environment on the judgement of room temperature or comfort. Two studies exposed participants to differently coloured walls [30] or entire rooms decorated in different hues [61] and participants had to estimate the temperature in the different settings. Their temperature estimates did not differ significantly between settings. It might be that the substantially different outcome variable of temperature estimates as opposed to comfort ratings underlies the different findings, indicating that people may be able to dissociate between comfort feeling and temperature estimates. This idea is supported by the notion that self-reported thermal sensation, thermal preference, and thermal comfort are qualitatively different entities [7]. Finally, Houghton et al. [33] made participants watch coloured screens illuminated by red, green, and white light (spectral composition not given) and found no effect on self-reported thermal comfort; however, luminance varied significantly across the three settings which might have confounded results.

Most important to the present investigations, are those studies that evaluated the effect of illumination colour on the sensation or judgement of temperature. However, again, results were ambiguous. Bennett and Rey [3] found that wearing coloured googles did not have any effect on the judgement of thermal temperature. Whilst wearing goggles, within some limits, has similar effects as changing the illumination, the authors themselves speculated whether the “washed-out” impression that the goggles produced might explain the absence of an effect. Berry [4], likewise, did not find any impact of illumination in five different hues on the point when participants reported feeling unpleasantly warm; however, participants were engaged in a task that supposedly measured the impact of differently coloured light on driving performance. Hence, one might speculate that when focusing on an unrelated but engaging task, awareness of our thermal comfort state is reduced. This speculation is corroborated by the fact that temperature conditions at point of expressed discomfort were of such values[1] that virtually every person would be expected to feel uncomfortable, i.e. a very high value, whereas one would expect half the people to feel uncomfortable already at a much lower level. However, several studies reported that observers either judged thermal temperature to be higher when illuminations had a warm colour [74,24], or preferred illumination colours (e.g. bluish) that compensated the temperature (e.g. warm) as predicted by the hue- heat-hypothesis [9]. In all of these studies, illumination per se was altered (i.e. not via goggles but via room lighting), and in none of the studies, participants had to estimate the room temperature in degrees. Instead, subjective comfort ratings [9,74] and temperature evaluations of the room ranging from hot to cold [74] were obtained, or temperature preferences estimated as indicated by adjusting the thermostat setting [24].

To summarize, existing research is somewhat ambiguous regarding a relationship between colour and perceived temperature/thermal comfort. Three conditions seem to be associated with the absence of an effect of colour on thermal perception: having to judge a room’s temperature in degrees as an outcome measure [30,61]; performing an engaging task [4], and manipulation of the colour of objects that are to be judged for their warmness [32,53]. Previous studied also suffered from methodological issues, such as insufficient control for varying luminance levels (e.g. Ref. [33,3]), not measuring temperature according to the standard BS EN ISO 7726 [38] (e.g. Ref. [61]), and not controlling for other factors known to impact on thermal comfort (e.g. Ref. [30]). Finally, none of the studies accounted for differences in ambient temperatures between session and/or participants in the analysis, even though acknowledging that there were such differences (e.g. Ref. [3]).

1.2. Introduction to thermal comfort

Thermal comfort is complex, and many factors impact on it that need to be considered when evaluating the hue-heat-hypothesis. In the literature related to thermal comfort, two very different approaches dominate: (a) the heat balance or predictive model of thermal comfort, and (b) the adaptive model of thermal comfort (for an overview, see Refs. [6,60]). In the heat-balance models, six factors predict the occupants’ overall satisfaction with the thermal environment as expressed by the Predicted Mean Vote (PMV): (1) ambient air temperature (T_a), (2) mean radiant temperature (T_r), (3) relative humidity (RH), (4) air velocity (V_a), (5) metabolic rate (met), and (6) clothing level (clo) [39,Annex D,23]; hence, these factors need to be controlled for when studying thermal comfort. Note that illumination does not feature as a factor impacting on thermal comfort in existing predictive comfort models in the tradition of Fanger.

Numerous studies found that participants were satisfied with thermal conditions outside the range as predicted by the PMV [16]. These findings fed into the evolution of adaptive models of thermal comfort in which factors beyond the heat-balance of a body are of importance, such as previous and current climatic experiences [55]. One of the main characteristics of the adaptive model is that indoor thermal comfort is associated to both indoor operative temperature and prevailing mean outdoor temperatures [17]. Having control over the environment also impacts on comfort experience [59]. Again, illumination does not feature as an impact factor but it could be integrated via psychological adaptation which “describes the extent to which habituation and expectation alter one’s expectation of and reaction to sensory stimuli” [17,p. 3].

Other impact factors on thermal comfort are gender, age, and weight. Thermal dissatisfaction is more often expressed in females than in males (e.g. Refs. [44,64]), and thermal comfort preferences can vary with age (e.g. Refs. [57,65]). Underweight participants have been shown to suffer more from cold extremities [54], and in general, weight and height are related to physiological parameters that in turn impact on thermal comfort (for an overview, see Ref. [35]).

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[1] For details on the Temperature Humidity Indicator that was used in this study, refer to https://www.google.com/patents/US3124002. Accessed 17.06.2015.

Table 1
Summary statistics on participant characteristics, Study 1.

	Light setting		Independent samples *t*-test
	2700 K	6500 K	
Mean age	25.5 (SD = 4.8)	23.9 (SD = 3.5)	ns
Mean level of clothing	.72 (SD = .16)	.67 (SD = .15)	ns
Mean metabolic rate	1.72 (SD = .38)	1.71 (SD = .28)	ns
Mean Body-Mass-Index	20.53 (SD = 1.98)	22.00 (SD = 2.55)	ns

The factors known to impact on thermal comfort need to be controlled for when assessing thermal comfort to test the HHH. These are radiant and ambient temperature, relative humidity, air speed, clothing level, and metabolic rate, gender, weight, and age.

1.3. *The current studies*

We used an experimental approach in a climate chamber to test if light impacts on thermal comfort. Our two studies overcame the main issue of previous studies of not controlling for (all) covariates that might impact on thermal comfort. In particular, we ensured:

- Careful control of all factors known to impact on thermal comfort: By testing in a climate chamber, we were able to control the environmental factors of radiant and ambient indoor temperature,[2] air velocity, and relative humidity, and measured temperature according to standard [38]. We also controlled for level of clothing between participants, metabolic rate, gender and Body-Mass-Index (only partly done in previous studies). Age range was restricted to 18–35 years in our studies; a range in which age effects may have little impact on thermal comfort [60,p. 223].
- Accounting for differences in ambient temperatures between participants and session by including (as the first study ever) ambient temperatures as a covariate in all analyses.

We employed multiple ways of measuring thermal comfort because as discussed above, different outcome measures might be differentially sensitive to any colour effect, with no effect present when asking for estimates of ambient temperatures. We reasoned that self-reported or observed discomfort is the outcome variable of greatest interest for potential application for energy savings. Hence in Study 1, standard thermal comfort surveys were used to assess thermal comfort [37], and in Study 2 an observational design where the experimenter noted if and when participants put on additional clothing. To our knowledge, no other study addressing the hue-heat-hypothesis has used an observational design. This outcome measure has the advantage of constituting an ecological valid variable: discomfort has then energy implications if it is so strong that participants act upon it which can neither be established with survey ratings nor temperature estimates. We chose ambient temperatures varying around those common in offices [13] again for reasons of ecological validity—if light mattered only at extreme temperatures, it would lose its potential for energy savings. We used a commercially available LED-lighting system to vary illumination, which could hence be easily implemented in buildings.

Finally, we used a design with continuously changing temperatures (from 20 °C to 24 °C or vice versa over a 60-min time period) instead of exposing participants to a constant temperature. This was done in order to ensure that every participant would be likely to experience a change in comfort with changing temperatures, containing a temperature range that would be likely uncomfortable in which light might have a mitigating effect.

2. Study 1

In the first study, comfort was assessed using standard thermal comfort surveys. Data collection took place between March and May 2014.

2.1. *Methods*

2.1.1. *Participants*

Participants were recruited through the subject pool of University College London (UCL). The study was approved by the UCL Ethics Committee and all participants provided written informed consent prior to the study. Payment was £8/h. Using the background survey, for each participant, we translated the reported metabolic rate into 'met' values as given in Annex B of Ref. [39], separately for each of the four time periods enquired about ('last ten minutes', 'between 20 and 10 min ago', 'between 30 and 20 min ago', 'between 60 and 30 min ago'). The values were then averaged across the four time periods. The items of clothing participants reported wearing were translated into a total score of 'clo' (clothing) level as defined in Appendix C of Ref. [39]. Each item was translated into its corresponding insulation value and those values were then summed up for each person. We calculated the Body-Mass-Index using the standard formula (e.g. Ref. [21]).

Of the 32 participants, 18 were male and 14 female; their distribution over the two light conditions was the same (nine males and seven females in each condition). Table 1 summarises participants' characteristics.

For the BMI, the difference was almost significant, $t(30) = -1.84$, $p = .08$. Hence, this variable was retained as a covariate in subsequent analysis.

2.1.2. *Experimental set-up and equipment*

Testing was carried out in the climate chamber which is an enclosed room in which temperature, humidity, and air velocity can be controlled. A white garden gazebo was erected in the climate chamber to prevent glare reflected from the stainless steel walls of the chamber interfering with the illumination. The gazebo was approximately 3.80 m long and 2.60 m wide with a height of around 2.60 m. Two chairs for participants were positioned in the corners of one of the long sides of the gazebo, with a third chair, centred opposite, provided for the experimenter (see Fig. 1).

An LED-based lighting system was mounted to the ceiling. The product ("ChromaWhite" from the company PhotonStar[3]) is fully tuneable in colour temperatures from 2700 K to 6500 K. Colour temperature or to be precise, correlated colour temperature (CCT) is the measure used to indicate the colour appearance of a light source and is measured in degrees Kelvin [5,62,75]. For the current work, it is sufficient to know that low colour temperature yields a

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[2] 'Ambient temperature' throughout the description of methods and results indicates 'indoor ambient temperature'; to avoid wordiness, we only write 'ambient temperature'.

[3] For further details, please see http://www.chromawhiteled.com/technology/chromawhite/. Accessed 15.06.2015.

Fig. 1. Photograph of experimental set-up for Study 1.

psychologically “warm” colour, i.e. yellow-reddish and high colour temperature a psychologically “cool” colour, namely blue.

The system consisted of four luminaires hanging from the ceiling at a height of 2.20 m, equidistant from both participant chairs. The system was controlled by the experimenter using a handheld controller. Spectral composition was measured using AvaSpec Avantes Fiber Optic Spectrometer. Fig. 2 shows the spectral composition of the two illuminations.

The colour temperature was set to 6500 K (a cold light) and 2700 K (a warm light) using the control device of the appliance. Those settings were the maximum and minimum, respectively, that the device was capable of producing; and produced distinctively different light. Measurements of the settings showed correlated colour temperature to be 6329 K (for the 6500 K setting) and 2892 K (for the 2700 K setting). For ease of communication, we will refer to the light settings as 6500 K and 2700 K. The CIE1931 [14] chromaticity coordinates of the blueish and yellowish-reddish illuminants were [.3163 .3269] and [.4485 .4140]. A Konica Minolta T 10 Illuminance metre was used to measure illuminance horizontally on the work plane (~800 mm), this was recorded as 550 lux for 2700 K, and 495 lux for 6500 K. The difference in illuminance between the two illuminants (55 lux) is about one just-noticeable difference or even less (according to reported Weber fractions, e.g. by Griebel and Schmid [31]), and hence highly unlikely to have a considerable effect on perception.

Ambient temperature and relative humidity were measured at four locations at four heights (1.6 m, 1.1 m, 0.6 m, and 0.1 m) in accordance with Ref. [38,Table 5], using 16 Hobo sensors (Onset HOBO U12-012) that were calibrated prior to usage and had a sampling rate of 1-minute. Two poles were put in the inside corners of the gazebo, one behind each participant, and two poles outside the gazebo. For each participant, the session temperature was calculated by averaging across sensors at three heights (1.1 m, .6 m, .1 m) at the respective pole in the corner behind.

2.1.3. Procedure

Upon arrival, the experimenter checked whether participants had conformed to instructions on how to dress for the experiment (i.e. shoes, socks, long trousers, and a long-sleeve shirt). If not, participants were asked to either put on items of clothing provided, or to take off some clothing (this was necessary for two participants).

Participants were then given information sheets about the experiment, signed the consent form, and filled in the background survey. The study was presented as testing the impact of different environmental conditions on thermal comfort, with no specific conditions mentioned. The whole preparatory period lasted about 20 min and took place in a windowless basement room just outside the climate chamber with lighting and temperatures constant across participants. In addition to information collection, the preparatory period ensured that all participants were adapted to a similar temperature and illumination before the experiment; and that they had been sitting still for about 20 min in order to achieve a similar level of pre-experiment metabolic rate.

After this period the participants were led into the climate chamber two at a time. During the experiment participants had to sit on the chairs provided and read material that they had brought themselves. Reading material was supposed to be leisure reading material, i.e. no course-work. Magazines were provided for those who did not bring any reading material. A conscious decision was taken not to prescribe the reading: the same material could have very different effects on different participants, which could in turn also impact on comfort. For the purpose of the study it seemed negligible that this decision might result in slight difference in photons meeting the eye: there are no grounds to expect any bias, i.e. participants under one light reading one type of material and those under the other light a different type of material, since readings were chosen beforehand. No participants reported suspecting the study related to lighting in the debriefing after the study.

2.1.4. Experimental design

Participants stayed in the climate chamber for 60 min. As a between-subjects variable, the light was set to either 6500 K or 2700 K. The air temperature decreased continuously from 24 to 20 °C (cooling cycle) or increased from 20 to 24 °C (warming cycle). Whilst this temperature range is relatively narrow, it encompasses the range of temperatures usually found in offices, and hence constitutes the temperature range of interest [13]. Relative humidity was kept at 50%. Air velocity was measured and was below the perceptual threshold of .1 m/s. Conditions were counterbalanced to ensure testing occurred equally often in the morning and afternoon in either light condition.

2.1.4.1. Outcome measure. Participants had to fill in thermal comfort surveys every 10 min. They were handed the sheets by the experimenter who collected them upon completion. The questions correspond to the ASHRAE standard scales for thermal comfort [37]. The five questions differ as to the aspect of the judgement (e.g. evaluative, preferential, localized, present, future, etc.) and to the object of the judgement (e.g. environment or person). The first three questions assess how the participants feel, distinguishing ‘between perception, present affective assessment (comfort/discomfort) and future preference’. The last two questions assess how participants judge the local environment, distinguishing between personal acceptability and tolerance. Table 2 shows the questions and answer scales of the survey, and specifies in the parentheses which aspect of comfort is assessed.

Annex B of the respective standard [37] gives guidance on data analysis and interpretation of results: the five survey questions are to be analysed separately as they assess different aspects of the subjective judgement. In addition, a review showed that when using the five survey questions as an indirect measure of acceptability of the thermal conditions, very different estimates resulted from the different questions, supporting the notion that the questions measure different aspects of thermal comfort [7].

2.1.4.2. Inclusion of control variables. Body-Mass-Index was used as a covariate in all analyses; age, clothing level, and metabolic rate were not used as covariates as they did not differ significantly between groups, and only varied over a very narrow range. Time of day when testing occurred was included as a factor in all analyses

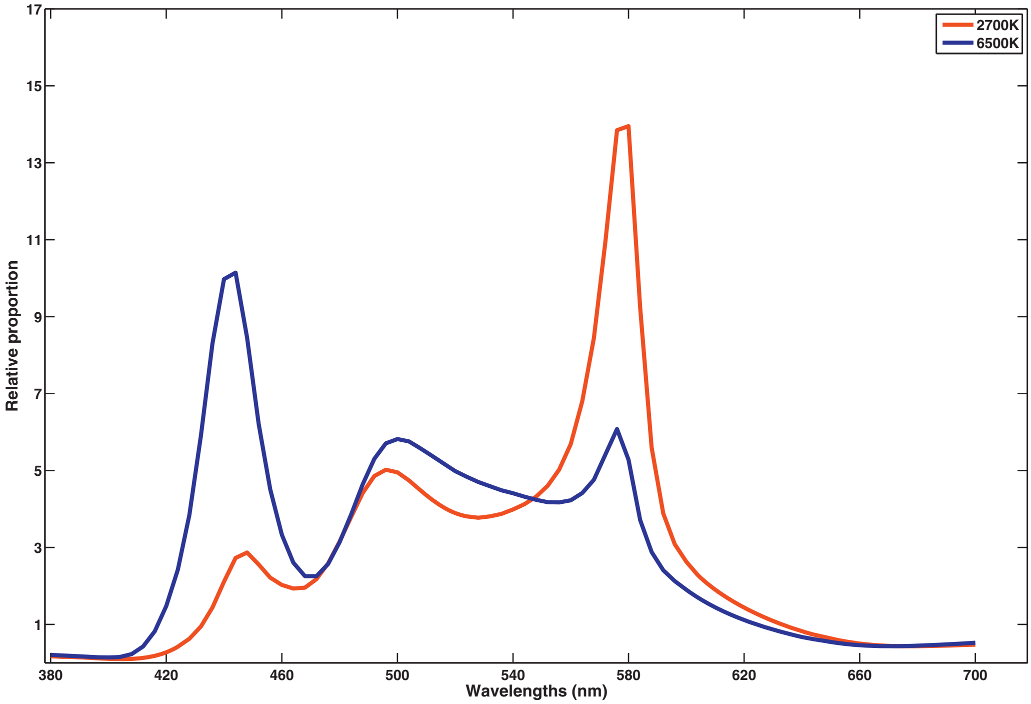

Fig. 2. Normalized spectral composition for the 2700 K and 6500 K light.

Table 2
The five survey questions used for assessing thermal comfort.

Question	Answer options (numeric coding)
(1) How are you feeling in this moment? ('Thermal perception')	Cold (1), Cool (2), Slightly cool (3), Neutral (4), Slightly warm (5), Warm (6), Hot (7)
(2) Do you find the current thermal condition...? ('Affective assessment')	Comfortable (1), Slightly uncomfortable (2), Uncomfortable (3), Very uncomfortable (4), Extremely uncomfortable (5)
(3) How would you prefer to feel? ('Thermal preference')	Much cooler (1), Cooler (2), Slightly cooler (3), Without change (4), Slightly warmer (5), Warmer (6), Much warmer (7)
(4) Taking into account your personal preference only, would you rather accept than reject this climatic environment? ('Personal acceptability')	Yes (1), No (2)
(5) Is this environment, in your opinion...? ('Personal tolerance')	Perfectly bearable (1), Slightly difficult to bear (2), Fairly difficult to bear (3), Very difficult to bear (4), Unbearable (5)

as different light settings could have a differential impact in the morning (session starting at 10.30 h) and afternoon (session starting at 15.00 h). Air velocity and relative humidity were not used as control variables, as the first one was below perceptual threshold and the latter one constant across time and participants.

We calculated the average temperature over the testing session for each participant to derive a person-specific mean temperature (called 'M_Temp'). This was done to take into account that the climate chamber did not perfectly reproduce the same temperatures in each session. The average session temperatures ranged over 1.3 °C between lowest and highest. To account for these differences, we used M_Temp as a covariate. We created an additional covariate, the difference between the temperature at any survey time-point and the mean session temperature for each participant. This person-centred temperature variable (called 'D_Temp'), hence indicates how temperatures changed at each survey time-point in relation to M_Temp (i.e. the mean session temperature) for each participant. Such an analysis is necessary because temperatures at the different survey time points were not reproduced identically for each participant and session; hence, this variation needs to be accounted for. For more details, see Ref. [2]. During the testing session, those times when individual participants experienced temperatures higher than their M_Temp, D_Temp was positive, where temperatures were lower than M_Temp, D_Temp was negative. Hence, a positive coefficient for D_Temp means that the outcome measure increases with increasing temperatures (or decreases with decreasing temperatures) whereas a negative coefficient for D_Temp means that the outcome measures decreases with increasing temperatures (or increases with decreasing temperatures).

2.1.5. Statistical tests

To analyse questions 1, 2, 3, and 5 (see Table 2), the MIXED procedure in SPSS was used. The MIXED procedure fits models more general than those of the general linear model procedure, allows correlated data and unequal variances, and makes it possible to model the participant-specific, repeated-measure covariate D_Temp (for details, see Ref. [67]).

We used Maximum Likelihood estimation and either used a first-order autoregressive (AR1) covariance matrix or an unstructured covariance matrix, whichever one was associated with lowest values on the Aikake Information Criterion (AIC), a measure of the relative quality of a statistical model and generally used for model selection.

As predictors we used the following factors: lighting (2700 vs. 6500 K), gender (male vs. female), time of day (AM vs. PM), and the covariates M_Temp and D_Temp. For the effect of lighting, one-sided testing was used given the clear expectation on direction of the effect. Pairwise post-hoc comparisons were Bonferroni-adjusted.

Two interaction effects were included in the model: the interaction between lighting and time of day, and between lighting and D_Temp. To assess a possible interaction effect, we calculated marginal estimated means of lighting with D_Temp 1.5 °C below the mean temperature of the session, at the mean temperature of the session, and 1.5 °C above the mean temperature of the session.

All predictors were modelled as fixed effects; the repeated measures design was modelled through using D_Temp as a repeated subject factor. MIXED tests the effect of each factor whilst controlling for all other factors.

For survey question 4 with its dichotomous outcome variable, we used the GEE procedure in SPSS, i.e. Generalised Estimation Equations (for details, see Ref. [36]). We modelled data with the assumption of a binomial distribution and a logit link. The same factors and interactions were modelled.

2.1.6. Missing data

For one participant, the temperature loggers had not worked. The data were imputed using mean imputation based on all other participants. Two participants had not provided body weight. Again, mean imputation was used to calculate the BMI based on either all male participants (for missing data on a male's body weight) or on all female participants (for missing data on a female's body weight).

2.1.7. Hypotheses

We hypothesized that thermal comfort would be greater under the 2700 K light than under 6500 K light in all questions (i.e. a main effect of light), and that there is likely to be an interaction effect. The interaction effect would mean that only at certain temperatures the light setting would impact on comfort, e.g. only at the lower ambient temperatures, comfort would be higher under warm light than cool light, whereas at the higher ambient temperatures comfort would not be impacted by light.

2.2. Results

The following series of figures shows the average responses with the standard error of the mean (SEM) to the different comfort questions (Fig. 3–7), with the accompanying text only highlighting significant effects. Statistical details for all analyses are shown in Table 3.

Fig. 3 shows the answers to the first question in the cooling cycle (a) and the warming cycle (b).

For the cooling cycle, participants felt significantly warmer under the light of 2700 K than 6500 K (estimated marginal means [EMS]: $M_{2700\,K} = 3.04$ [SE = 0.17]; $M_{6500\,K} = 2.639$ [SE = 0.17]). Lower ambient temperatures (D_Temp, M_Temp) were associated with lower ratings, more towards 'cold', on the scale. A higher BMI was associated with higher ratings on the scale ($b = .12$).

For the warming cycle, the main effect of lighting was not significant. The main effect of D_Temp was significant. In addition, there was a significant interaction between lighting and time of testing: when testing was done in the morning, comfort was significantly higher under the light of 2700 K ($M_{2700\,K} = 3.75$, SE = .26) than under light of 6500 K ($M = 2.77$, SE = .28). When testing was done in the afternoon, comfort did not differ under the two light settings.

Fig. 4 shows the average responses to the second question.

For the cooling cycle, the effect of lighting was significant with participants judging the environment as more thermally comfortable under the light of 2700 K than 6500 K (EMS: $M_{2700\,K} = 1.47$ [SE = .09]; $M_{6500\,K} = 1.71$ [SE = .09]). The effect of D_Temp was also significant. The effect of M_Temp, the average temperature per session, was also significant.

For the warming cycle, the effect of lighting was also significant, with participants judging the condition as more comfortable under 2700 K than 6500 K (EMS: $M_{2700\,K} = 1.15$ [SE = .11]; $M_{6500\,K} = 1.51$ [SE = .10]). The effect of D_Temp was highly significant, i.e. temperatures increase over the session, the score moves towards finding the environment more comfortable. The effect of M_Temp was also significant, i.e. participants exposed to an environment with higher mean session temperatures felt more comfortable. The main effect of testing time was also significant: In the afternoon testing session, the environment was judged as more comfortable (EMS: $M_{am} = 1.52$ [SE = .10]; $M_{pm} = 1.14$ [SE = 0.10]).

The interaction of light and D_Temp was significant. We ran pairwise comparisons with D_Temp 1.5 °C below the mean of the

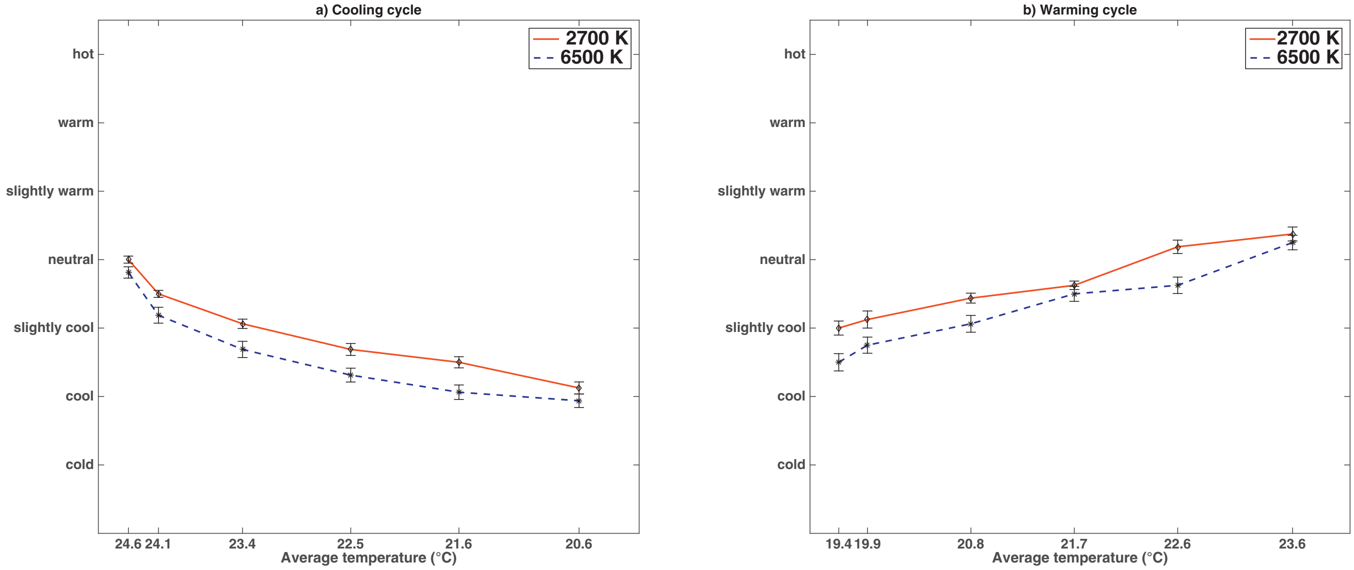

Fig. 3. Average responses to the first survey question ("How are you feeling in this moment?") under 2700 K and 6500 K in the cooling cycle (1a) and the warming cycle (1b).

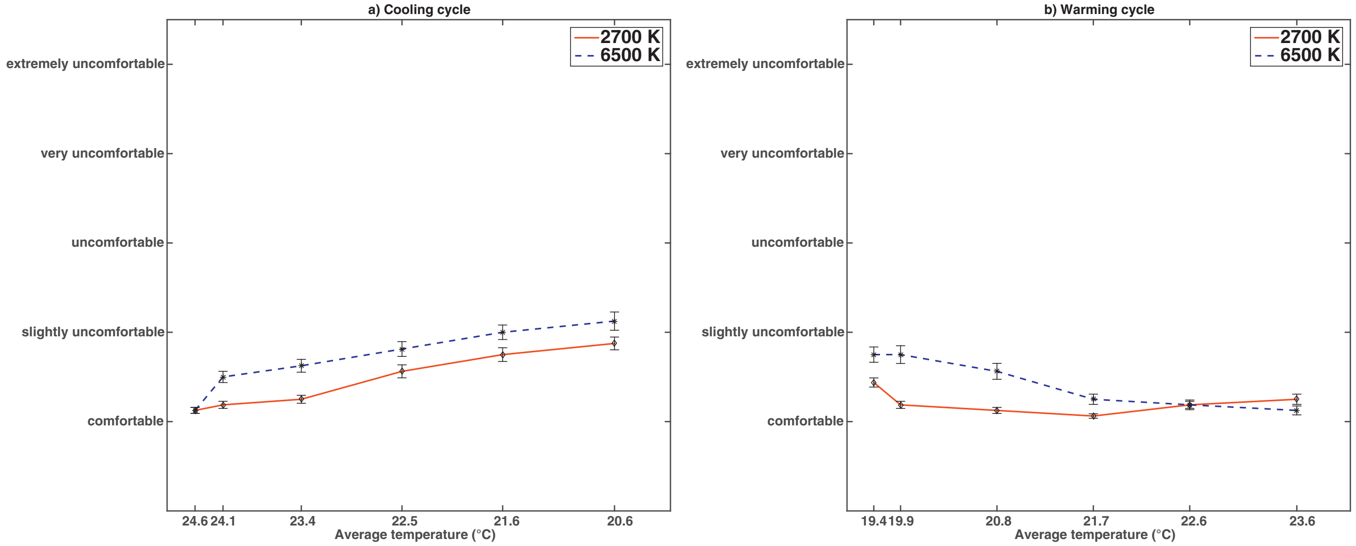

Fig. 4. Average responses to the second survey question “Do you find the current thermal condition [comfortable–extremely uncomfortable]?” in the cooling cycle (3a) and the warming cycle (3b).

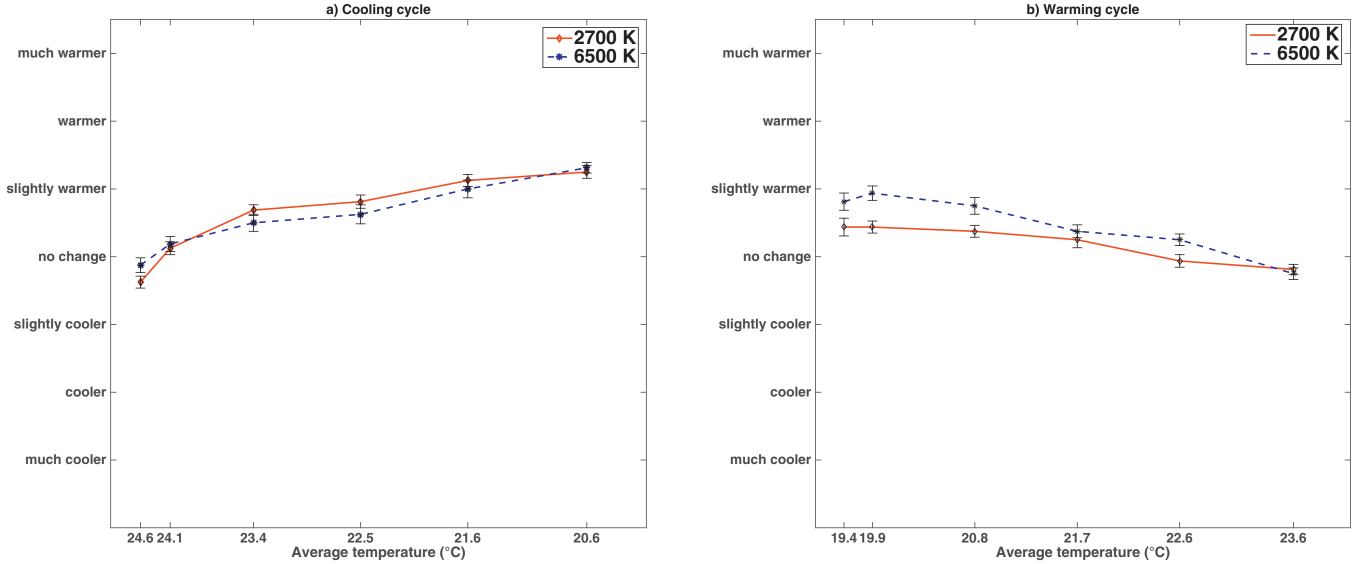

Fig. 5. Average responses to the third survey question “How would you prefer to feel?” under 2700 K and 6500 K in the cooling cycle (4a) and the warming cycle (4b).

session, 1.5 °C above the mean, and at the mean. For a D_Temp of −1.5 °C, below the mean, comfort was significantly higher under 2700 K than 6500 K (EMS; $M_{2700\,K} = 1.20$ [SE = .15]; $M_{6500\,K} = 1.77$ [SE = .15]). At the average temperature, light had significant effect on comfort, $M_{2700\,K} = 1.15$ (SE = .11) and $M_{6500\,K} = 1.51$ (SE = .15). However, at the temperature of 1.5 °C above the mean, the effect of light was not significant.

Fig. 5 shows the responses to the third question in the survey.

For the cooling cycle, only the effects of D_Temp and M_Temp, were significant, indicating that as temperatures decreased (D_Temp decreasing), people moved towards wanting to feel warmer, and that in sessions with higher average temperatures people expressing a lower want of feeling warmer.

For the warming cycle, participants wanted to feel significantly warmer under 6500 K than under 2700 K (EMS: $M_{2700\,K} = 4.19$ [SE = .15]; $M_{6500\,K} = 4.58$ [SE = .15]). The effect of gender was also significant, with females preferring significantly stronger to feel warmer (EMS: $M_{female} = 4.71$, SE = .15; $M_{male} = 4.06$; SE = .13). Finally, the effect of D_Temp was significant.

Fig. 6 shows the response to the fourth question in the comfort survey about the acceptability of the thermal environment. A ‘yes’ reply, meaning that participants would rather accept than reject the environment, was coded as 1 and a ‘no’ reply as 2.

In the cooling cycle, acceptance was significantly higher under 2700 K than 6500 K (EMS: $M_{2700\,K} = .76$, SE = .05; $M_{6500\,K} = .58$, SE = .06). The effect of D_Temp was also significant. Hence, higher temperatures were associated with moving more towards the ‘yes’ answer.

In the warming cycle, again, acceptance was significantly higher under 2700 K than under 6500 K (EMS: $M_{2700\,K} = .91$, SE = .04; $M_{6500\,K} = .78$, SE = .05). The interaction between light setting and time of testing was significant: When testing in the morning, the mean rating under warm light ($M_{2700\,K} = .96$, SE = .03) was significantly higher than under the cold light ($M_{6500\,K} = .60$, SE = .08). In the afternoon, testing was not impacted by light setting. When looking at average rating under 2700 K, it was significantly higher in the morning than the afternoon, $M_{am} = .96$ (SE = .03), $M_{pm} = .83$ (SE = .06). When looking at average rating under 6500 K,

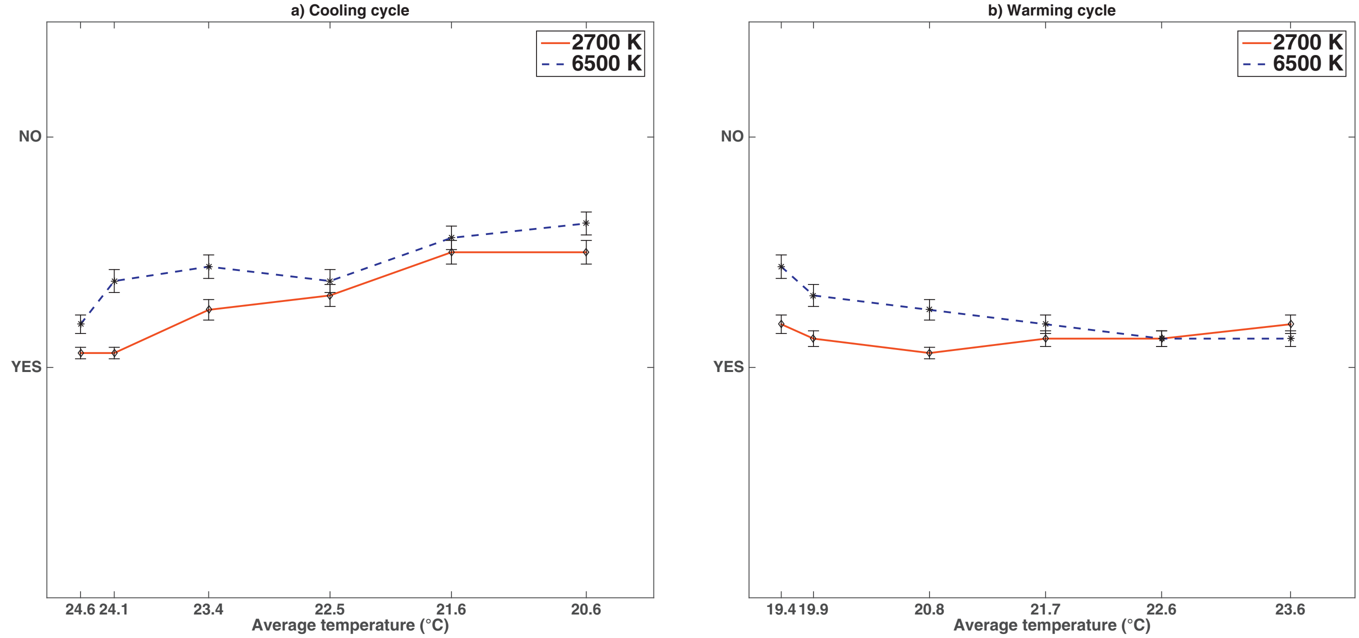

Fig. 6. Average responses to the fourth survey question "Would you rather accept than reject this thermal environment?" under 2700 K and 6500 K in the cooling cycle (5a) and the warming cycle (5b).

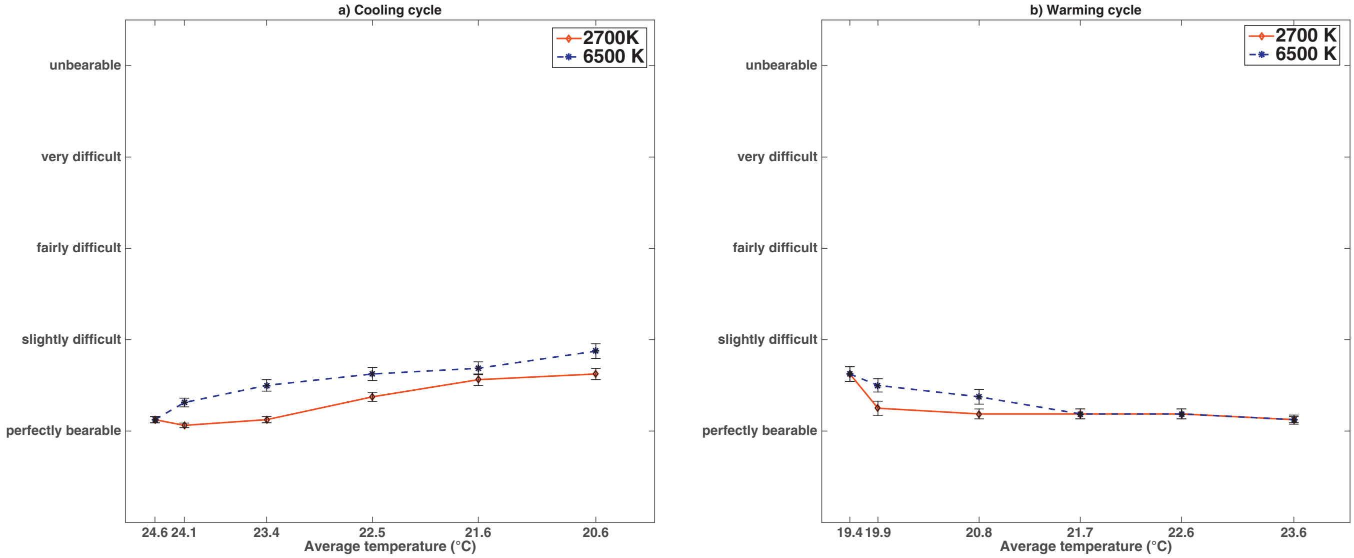

Fig. 7. Average responses to the fifth survey question "Is this environment [perfectly bearable–unbearable]?" under 2700 K and 6500 K in the cooling cycle (6a) and the warming cycle (6b).

the opposite pattern emerged: Rating was significantly higher in the afternoon than in the morning, $M_{am} = .60$ (SE = .08), $M_{pm} = .89$ (SE = .05).

Fig. 7 shows the response to question 5 on how bearable the condition was on a 5-point scale from perfectly bearable (1) to unbearable (5).

In the cooling cycle, participants judged the environment as less unbearable under 2700 K than 6500 K (EMS: $M_{2700\,K} = 1.08$, SE = .09; $M_{6500\,K} = 1.26$, SE = .1). The main effect of D_Temp was also significant: lower temperatures mean an increase in response score, i.e. finding the environment more difficult to bear.

In the warming cycle, only the effect of D_Temp was significant: lower temperatures were associated with a higher score, i.e. finding the environment more difficult to bear.

Table 3 shows the statistics details for significant effects of all five questions in both the cooling and the warming cycle.

To summarize, in seven of the 10 units of comparison (five questions in two temperature conditions), a main effect of light existed in the direction of the hypothesized finding of greater comfort under the light of 2700 K within the temperature band tested. In two comparisons, an additional interaction effect of light setting and temperature was found, limiting the effect of light to the lower temperature range. The results lend some support to the hue-heat-hypothesis. As not all questions showed an effect as hypothesized, this underlines that the questions were addressing qualitatively different aspects of comfort perception which were differentially affected by light. Moreover, these surveys were initially designed for constant temperature conditions—not dynamically changing

Table 3
Statistics for all analyses, Study 1.

	Cooling cycle				Warming cycle			
Question 1	*F*	df	*b*	*p*	*F*	df	*b*	*p*
Light	2.88	1,32.52		.049				ns
Time of day				ns				ns
Gender				ns				ns
M_Temp	5.11	1, 32.38	.79	.031				ns
D_Temp	11.54	1, 30.51	.49	<.001	47.11	1, 31.35	.4	<.001
BMI	4.82	1, 32.44	.12	.035				ns
Lighting × time of day				ns	6.23	1, 31.35		.018
Lighting × D_Temp				ns				ns
Question 2	*F*	df	*b*	*p*	*F*	df	*b*	*p*
Light	3.21	1,39.4		.045	5.19	1,31.83		.015
Time of day				ns				ns
Gender				ns				ns
M_Temp	5.97	1,50.02	−.42	.018	7.67	1, 32.12	−.65	.009
D_Temp	813.48	1, 43.12	−.23	.001	9.44	1, 31.66	−.18	.004
BMI				ns				ns
Lighting × time of day				ns				ns
Lighting × D_Temp				ns	4.71	1, 31.66		.038
Question 3	*F*	df	*b*	*p*	*F*	df	*b*	*p*
Light				ns	3.25	1, 62.04		.038
Time of day				ns				ns
Gender				ns	9.61	1, 62.74		.003
M_Temp	5.76	1, 32.01	−.96	.022				ns
D_Temp	65.44	1, 29.95	−.34	<.001	5.24	1, 53.49	−.27	.022
BMI				ns				ns
Lighting × time of day				ns				ns
Lighting × D_Temp				ns				ns
Question 4	Wald-X^2	df	*b*	*p*	Wald-X^2	df	*b*	*p*
Light	5.04	1		.013	3.96	1		.024
Time of day				ns				ns
Gender				ns				ns
M_Temp				ns				ns
D_Temp	19.76	1	.42	<.001				ns
BMI				ns				ns
Lighting × time of day				ns	10.34	1		.001.
Lighting × D_Temp				ns				ns
Question 5	*F*	df	*b*	*p*	*F*	df	*b*	*p*
Light	3.99	1,56.99		.036				ns
Time of day				ns				ns
Gender				ns				ns
M_Temp				ns				ns
D_Temp	10.33	1, 43.94	−.17	.002	18.53	1, 32.21	−.12	<.001
BMI				ns				ns
Lighting × time of day				ns				ns
Lighting × D_Temp				ns				ns

conditions (however, given a lack of alternative, they are widely used in dynamic contexts, too). Hence, it might be that the survey questions were inadequate in assessing thermal comfort in changing conditions. In light of this reservation on the applicability of the dependent variable instrument in dynamic conditions, in Study 2 an observation design was used to register changes in clothing following changes in temperature which is assumed to also have greater ecological validity. For energy consumption, it is important to know when a condition becomes sufficiently uncomfortable for a person to make a change to some external variable—which in this case was restricted to changes in clothing, but in real life could just as well be changes in thermostat setting.

3. Study 2

The following section first provides additional information about the methods of Study 2 before showing the results.[4]

3.1. Methods

3.1.1. Participants

The sample consisted of $N = 32$ participants (23 female, nine male). Whilst the gender balance was unequal in this study, females and males were equally distributed across the two lighting settings (2700 K: 5 males, 11 females; 6500 K: 4 males, 12 females), as

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[4] Parts of this study have been presented at the Conference “Experiencing Light 2014*: International Conference on the Effects of Light on Wellbeing*” and are published as a short conference paper in the Proceedings [34].

Table 4
Summary statistics on participant characteristics, Study 2.

	Light setting		Independent samples *t*-test
	2700 K	6500 K	
Mean age	23.9 (SD = 3.0)	22.9 (SD = 1.9)	ns
Mean level of clothing	.60 (SD = .10)	.56 (SD = .09)	ns
Mean metabolic rate	1.83 (SD = .49)	1.69 (SD = .28)	ns
Mean Body-Mass-Index	21.20 (SD = 2.50)	22.25 (SD = 3.38)	ns

shown by a Chi-Square test. Table 4 summarises the basic participant characteristics. Despite no significant difference in BMI, the variable was used as covariate given its significance in the first study.

3.1.2. Procedure and measurements

In addition to being told what to wear, participants were instructed to bring additional items of clothing to the testing session, namely a sweater or light jumper, and a light jacket. During the preparatory period, the experimenter positioned the items of clothing and an additional blanket for each subject in the climate chamber on a chair opposite to each participant at an equal distance for each participant. The climate chamber was divided using a black screen so that participants would be unable to observe each other.

After the preparatory period, participants were led into the climate chamber. The experimenter repeated that the temperature in the room might change and that if they felt cold they could put on additional items of clothing.

The experimenter was equipped with a stopwatch and recorded when participants put on clothing, and what they put on (outcome measures).

3.1.3. Statistical tests

We used the MIXED procedure in SPSS, again with Maximum Likelihood Estimation. Fixed effects were the factors lighting, gender, time of testing, the covariates BMI and average session temperature (M_Temp), and the interaction of lighting and time of testing. Note that D_Temp was not used as a covariate since no repeated measures of the comfort survey were collected.

3.1.4. Hypotheses

In detail, the dependent variables were: (1) total number of clothing item put on, and (2) ambient temperature in climate chamber when first item of clothing was put on. We hypothesized that participants would put on extra items of clothing earlier, i.e. at higher ambient temperatures, under the light of 6500 K than under 2700 K, and would put on more items of clothing in total under the light of 6500 K than 2700 K.

3.2. Results

3.2.1. Total items of clothing put on

We first analysed how many participants put on extra clothing under each of the two light settings (Fig. 8). Note that the categories are inclusive, i.e. a participant who put on two items of clothing will be counted both for the “1+” and “2+” category. Fig. 8 shows that more participants put on extra clothing under the light of 6500 K than under 2700 K. Only one person put on two or more items under the light of 2700 K but nine persons under 6500 K.

The observation of less clothing needed under the light of 2700 K was confirmed through statistical analysis. The main effect of light was significant, $F(1, 32) = 4.30$, $p = .023$. The estimated marginal means were $M_{2700\,\mathrm{K}} = .73$ (SE = .18) and $M_{6500\,\mathrm{K}} = 1.25$ (SE = .19). Hence, participants put on significantly more items of clothing under the ‘cold’ light of 6500 K than under 2700 K. The main effect of gender was close to significance, $F(1, 32) = 3.75$, $p = .062$, with a trend of more clothing being put on by female participants. None of the other factors or interaction were significant.

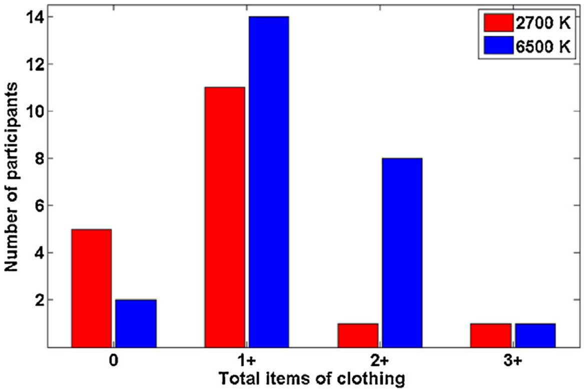

Fig. 8. Total items of clothing put on under 2700 K and 6500 K.

There was no difference in what item of clothing participants used first. Across conditions, if any clothing was put on, the jumper was used first most often (52%), followed by the jacket (38%).

3.2.2. Temperature of putting on extra clothing

We analysed if participants put clothing at higher ambient temperatures (i.e. after a short time period in the chamber) under the cold than the warm light. This analysis is somewhat problematic because it needs to exclude those participants who did not put on any clothing and hence ignores that some people would have put on clothing only after more than 60 min. For two or more items, statistical analysis was not possible as only one participant put on more than one item of clothing under the warm light (as opposed to 8 under cold light).

For both light settings the first item of clothing was put on at an average of 21.26 °C, i.e. there was no main effect of light. The main effect of gender was highly significant, $F(1, 25) = 11.33$, $p = .002$. Females put on the first item of clothing at an average of 22.16 °C (SE = .24) and males at the significantly lower temperature of 20.36 °C (SE = .45). For those 8 participants under the cold light who put on a second item of clothing, the average temperature was 20.9 °C; they were all female.

Study 2 showed a significant effect of light as hypothesized, with participants putting on more clothing under the cold-appearing light than the warm-appearing light. It also showed the importance of gender in thermal comfort perception.

4. General discussion

Below, we summarize our results, and state limitations of our studies and necessary further research. We then discuss possible ways how light might impact on thermal comfort, and implications for models of thermal comfort.

4.1. Summary and implications of the studies

Our studies used a carefully controlled experimental design to test if the colour temperature of the illumination, operationalized here as 6500 K (‘cold’) vs. 2700 K (‘warm’), affected thermal comfort, either assessed by survey responses (Study 1) or observed by changes in clothing (Study 2). Contrary to other studies, we measured and modelled ambient temperatures on a per-subject level and accounted for other potential covariates. In addition, our study used ambient temperatures that are similar to those found in offices [13], increasing the likelihood of transferring findings into real-world settings.

In Study 1, a main effect of light on thermal comfort was present in seven out of ten possible conditions—with higher ‘comfort ratings’ under the warm light of 2700 K than under the cold light of 6500 K. In Study 2, participants put on significantly more items of clothing under cold light than warm light. The fact that not all questions of the comfort surveys used showed an effect as hypothesized indicates that the questions indeed measure substantially different aspects of comfort. The next step would be to identify which question is most strongly related to occurrence of a discomfort response. The observation study showed a significant effect of light as hypothesized, and can be considered as having greater ecological validity by measuring an outcome that constitutes a possible reaction in everyday life, i.e. changing clothing level to achieve or maintain thermal comfort. Whilst knowing that one is observed might alter behaviour [45], there is no reason why such an effect would be different in the two light conditions; participants were naïve to the study and were only tested in one condition. Hence, the differential effect of cold-vs. warm appearing light on comfort behaviour is not attributable to the mere fact of being observed.

Hence, we conclude that the results show some support for the hue-heat-hypothesis. Dynamically tuning the colours of lighting, now commercially technically viable using LED technology, may prove to be a tool for energy reduction in buildings by decreasing the energy needed for cooling and heating. Our findings support those earlier studies most similar to our approach [9,24,74] who had also manipulated the ambient illumination, and found a weak but significant effect of light on thermal perception or comfort when participants were not performing an otherwise engaging task. The effect of gender was significant in one survey question, and was related to the timing and prevalence with which participants put on clothing (Study 2)—with females ‘feeling the cold more’; however, the sample of males in Study 2 was very small (*N* of 4 and 5, respectively). This gender effect is in line with earlier research (e.g. Refs. [44,64]). Some evidence suggests that temperature perception might vary as a result of differences in thermoregulation between males and females mostly because of anthropometric differences in body fatness and the ratio of body surface area to size (e.g. Refs. [51,71]). Other authors suggest that differences in thermal comfort and temperature preference cannot be explained by physiological gender differences but are more likely to reflect cultural and psychological effects [43]. Irrespective of what brings about the observed gender differences in our studies and in previous research [44,64], another strategy for reducing space heating and cooling in the office would be to offer ‘warm’ and ‘cool’ zones where people could choose to sit depending on their preference.

4.2. Limitations of our studies and further research

Our study tested only a narrow temperature range (even though the one with greatest ecological validity for office settings) and two light settings in a highly controlled environment. Also, the sample was limited in the age range tested; it might be, given that comfort preferences vary with age (e.g. Refs. [57,65]), results would differ in a sample with a different age structure. Further research needs to define the magnitude of the effect, and also determine the exact range of ambient temperatures in which light impacts on thermal comfort, in particular for high temperatures., and also variations of colour temperature of the illumination.

Also, it has to be seen if the effect remains in a real-world setting and what energy savings could be realised. Participants in our study did not have to perform any demanding tasks, and were under no time pressure. It is noteworthy that in the only previous study in which differential illumination did not impact on thermal perception [5] participants were engaged in a meaningful task, i.e. a driving task. Hence, it could be that when people are concentrating intently on a task, they would be much less aware of changes in light and temperature. In addition, in many workplaces, there are multiple other sources of light, e.g. emitted from display screen equipment and of course daylight. From a technological standpoint, it should be possible to measure and account for light from multiple sources, integrating colour spectrum data from sensors into lighting control algorithms. However, our study had excluded displays and daylight and hence, it cannot be stated that controlling for light emitted from displays and for daylight would work well enough to retain the effect of light on comfort. Such sensor data would need to detect the lighting conditions experienced by users and make compensations to controllable lighting sources in real time in order to balance the colour field experienced by those users. Even with such technologies in place, the user might still experience considerable variability in their light colour field as their vision wanders, and this variability may be sufficient to mask any impact of light on thermal comfort. Also, the possible energy savings need to be quantified, separately for the heating and cooling season. One might speculate that potential savings are lower in summer during the cooling season as less indoor lighting would be used, i.e. giving less opportunity to impact on thermal comfort through illumination. Also, the temporal stability needs to be tested; the effect of light on comfort might wear off after prolonged exposure. In that case, the main merit of using light to impact on comfort would rather lie in the area of reduction of power in situations of high power demand and potential overload of the local grid. Being able to turn off air conditioning or heating (assuming electrification of heat) without compromising comfort would be of benefit for grid stability.

Furthermore, it would have to be established that in an office context, the differentially coloured illumination does not negatively impact on mood or performance (e.g. Refs. [22,50]).

Finally, research should also test whether it is indeed the case that estimates of room temperatures (as opposed to comfort perceptions) are not affected by colour of the environment/the illumination as speculated in the introduction. This would give important methodological insight and in addition reveal how different perceptions around comfort and temperature might dissociate.

Despite these limitations, the results encourage further research into the hue-heat-hypothesis in particular in more applied settings to test for actual energy saving potential. Even small effects could potentially result in significant savings given that people spend most of the day indoors [69]. Non-domestic buildings account for 18% of total carbon emissions, 46% of those for space heating, and 11% for ventilation and cooling, and 23% for lighting [10], i.e. more carbon emissions are due to controlling temperatures within a narrow range The contribution of lighting to carbon emissions is likely to reduce given the increasing widespread installation of energy-efficient LED-lighting whereas in particular cooling requirements are forecasted to increase given the changing climate and rising incomes [40]. In addition, the recent advances in LED lighting (e.g. Ref. [56]), including increasing ease with which colour temperature can now be manipulated, now make practical implementation of such systems commercially feasible. How to ensure that such systems are best invested in and taken up by the private sector, is yet another open research question [66].

4.3. *What is a potential pathway for the impact of light on thermal comfort?*

As discussed in the introduction, people have colour-temperature associations [26,58] which in turn might bring about a link between colour and perception of ambient temperature. This might be due to certain colours in the environment being linked to different temperatures, such as the red glow of a fire to heat, and the bluish colour of ice to cold [72]. The association between certain colours and temperatures might also be strengthened by the relationship between the colour temperature of daylight and ambient temperature. The colour temperature of daylight varies depending on the season, daytime, and overcast [29,46,47,68]. One might speculate that colours at higher colour temperature generally tend to be more frequent in conditions of comparatively low ambient temperature, such as overcast skies, when the sun is low and during winter. The colour temperature tends to drop the clearer the sky, the closer the sun to the zenith, and during summer, i.e. when ambient temperature tends to be comparatively high. As a result, human observers might learn to associate the yellowish hues at the bottom of the daylight axes with warm temperatures, and bluish hues at the end of the daylight axes with cold temperatures.

The observed findings of differential comfort ratings and behaviours could also be a physiological effect, e.g. via metabolic rate. To be able to explain our findings, the light of 2700 K with a peak at 630 nm would have needed to lead to a physiological response for preventing or delaying the onset of thermal discomfort.

However, studies looking at the relationship between colour temperature and physiological responses have found that light with a predominance of short wavelengths, around 430 nm, are generally more stimulating and arousing (e.g. Refs. [8,12,70]), reactions one might associate with increased metabolic rate and hence potentially greater thermal comfort. Intrinsically photoreceptive ganglion cells with the photopigment melanopsin might be of importance in this context. They are involved in regulation of circadian rhythms, body temperature, and melatonin expression, and are most sensitive in the short wavelength part of the visual spectrum which implies that they should be most sensitive to bluish light (e.g. Refs. [12,49,52,25,18]). However, the illuminance of the lights used in the present study was so high that differences in spectral composition are small compared to the overall strongly stimulating effect of both lights, at low and high colour temperature [25,63]. More importantly, even if these lights have sufficiently different effects on those melanopsin-containing receptors the effect would contradict those observed here: bluish light should rather have a stimulating effect on metabolic rate than reddish or yellowish light, and hence give rise to a perception of feeling warmer. For these reasons, it seems rather unlikely that these melanopsin-containing receptors are at the source of the effect of hue on the perception of warmth, as observed in the present study, making a psychological effect more plausible. The time course of the effect of light on thermal comfort might also be indicative of what mediates this effect—if the effect is purely psychological, it might be very short-lived, because the normal physiological responses to a lower external temperature might override the psychological effect quickly.

4.4. *Illumination in models of thermal comfort?*

Illumination is not currently accounted for in either the heat-balance models of thermal comfort or in the adaptive approach but given our results, they might have to be expanded to incorporate effects of light. In the adaptive models, light could impact on thermal comfort via psychological adaptation which “describes the extent to which habituation and expectation alter one’s expectation of and reaction to sensory stimuli” [17,p. 3]. The adaptive model does not have equations to predict thermal comfort; but when considering comfort in buildings, light should be considered. The heat-balance model, given its physiological basis, could only incorporate an effect of light on thermal comfort through changes in metabolic rate. If further research supported the effect of light on thermal comfort across situations and time, it might have to be considered as an additional independent factor, leading to a revision of the current six-factor predictive model.

Acknowledgements

Funding was provided by Research Councils UK (RCUK) Centre for Energy Epidemiology (EP/K011839/1) and the Cisco Future Cities Project. CW was supported by ERC Advanced Grant FEEL No. 323674 to J. Kevin O’Regan.

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