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Effects of light and ambient temperature on visual and thermal appraisals

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Abstract: More than one third of a buildings' energy consumption is designated for heating and cooling. Therefore, allowing more variations in the indoor temperature provides an energy saving potential. Additionally, these variations are expected to have beneficial health effects on the building occupants. To compensate for potential discomfort amongst them due to these temperature variations, LED lighting may be used as light could influence thermal responses via cortical and sub-cortical brain regions.

Two laboratory studies were performed to examine how different light conditions can influence both visual and thermal appraisals. Temperature was manipulated between these studies: the first was in a thermoneutral environment (21 °C) whereas the latter was performed in a mild cold environment (17 °C). In contrast, light was manipulated within the studies. Participants came to the laboratory on multiple days, during which they were exposed to different light conditions in terms of both correlated colour temperature and intensity. Participants evaluated their visual and thermal experiences repeatedly throughout the session.

We can conclude that visual and thermal comfort are closely related. These findings could be applied in office environments to save energy by controlling the temperature less strictly and compensating potential thermal discomfort with visually comfortable light settings.

Keywords: Cross-modal effects, thermal appraisals, visual appraisals, temperature, light

1. Introduction

More than one third of the global energy consumption in the 21st century is taken up by buildings (*Energy Efficiency: Buildings*, no date). Space heating and cooling have been indicated by the International Energy Agency (IEA) to offer the most potential for energy savings in buildings. Less use of heating and cooling systems, however, is likely to lead to an indoor environment with a variable temperature instead of a constant one. Previous studies have shown that these variations can be beneficial for energy metabolism and human health (van Marken Lichtenbelt et al., 2017). However, due to this variation, office workers might experience thermal discomfort, especially before acclimatization (Hanssen et al., 2016). Changes in light intensity (Kim and Tokura, 2007) and/or correlated colour temperature (CCT; Candas and Dufour, 2005) may help relieve this short-term discomfort, and additionally, light has the potential to benefit health and productivity. This points to the relevance of studying interactions between climate and light in indoor settings.

Mogensen and English (1926) were the first to refer to a widespread belief of apparent or psychological warmth of colours. Over the years, this belief has been formulated as the hue-heat hypothesis, which associates blue(ish) colours and light to the experience of coolness, whereas red(dish) colour and light are related to the experience of warmth. Scientific evidence for this hypothesis is, however, mixed (e.g. Winzen, Albers and Marggraf-Micheel, 2014; Huebner et al., 2016; Ziat et al., 2016; Chinazzo et al., 2018; te Kulve, Schlangen and van Marken Lichtenbelt, 2018). Another cross-modal psychological association through which light is thought to influence thermal appraisals is the association of bright light with the sun, and therefore an environment may feel warmer in bright light compared to dim light (Xu and Labroo, 2014).

Visual-thermal interactions were investigated in terms of subjective evaluations in a correlational field study by Chinazzo et al. (2018). No statistically significant correlation between light intensity and thermal sensation was reported. However, when splitting the data in three slightly different temperature levels, they did find a small correlation between illuminance and thermal sensation suggesting that, in a relatively cool environment in summer, people do experience a higher thermal sensation when they are in bright light compared to dim light, in line with the cross-modal association described above. Remarkably, the thermal satisfaction in cool and neutral environments did not covary with illuminance. Only in a relatively warm environment the thermal satisfaction was significantly higher in illuminances above 300 lux compared to illuminances below 300 lux. The authors tentatively attributed these findings to thermal expectations induced by the illuminance level (Chinazzo et al., 2018), but as the study was purely correlational, this theory remains to be tested.

Te Kulve et al. (2018) studied similar interactions of light and temperature in a controlled laboratory environment, which could give more insight in explanatory mechanisms. They found an effect of light on thermal experience in a cool environment. A higher CCT of the light was associated with more self-assessed shivering compared to a lower CCT, which is in line with the hue-heat hypothesis. However, thermal sensation and comfort were not affected by the CCT of the light. Brightness of the light did not change the thermal perception of the environment either. In the warm and neutral thermal environments, no statistically significant effects of light - CCT or light intensity - on thermal perception were reported (te Kulve et al., 2018).

Apart from these cross-modal psychological associations that originate largely in cortical brain areas, the subcortical brain region is involved in both visual and thermal comfort evaluations. Correlational analyses by te Kulve et al. (2018) showed that the change in visual comfort was related to a change in thermal comfort in both the cool and the warm environment, which might be explained by these shared origin in the subcortical brain region. This finding further builds evidence for a relationship between light and thermal perception, while suggesting an alternative mechanism tying perception of visual and thermal comfort together. However, still the evidence is limited and any causality in this relationship of visual and thermal comfort is unknown. These findings imply that in uncomfortable thermal environments, the lighting can potentially be used to change visual comfort, and thereby also thermal comfort.

The Chinazzo et al. (2018) and te Kulve et al. (2018) studies report merely modest effects, on only a selection of the variables, and solely in non-neutral thermal environments. The findings of these studies hint towards interesting applications of the interaction between light and temperature perception, however, more research on the interrelationships between these factors is required before it can be employed in real office environments. The current study continues the line of research on cross-modal effects of light on temperature perception. The main research question is:

What is the effect of light on thermal perception?

Based on prior research on the hue-heat hypothesis (Candas and Dufour, 2005) and the association with sunlight (Xu and Labroo, 2014), it is hypothesized that both warm and bright light increase the thermal sensation.

The following research questions were formulated to further investigate the dependencies of the effect of light on thermal perception.

To what extent is this effect of light intensity and CCT moderated by the ambient temperature?

Based on the work by Chinazzo et al. (2018) and te Kulve et al. (2018), we expect that the effects are more pronounced in the mild cold environment compared to a neutral environment.

How do thermal and visual comfort relate?

The relationship between visual and thermal comfort as described in the work by te Kulve et al. (2018) predicts that in case of an increase in visual comfort, thermal comfort might also increase. Therefore, we expect a positive relationship between visual comfort and thermal comfort.

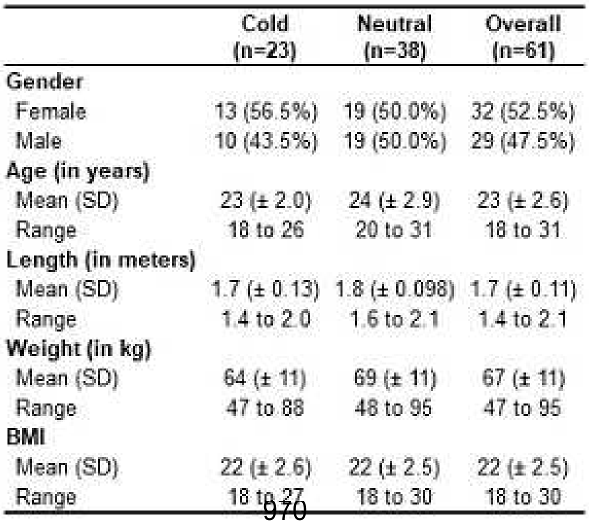
2. Method

Two laboratory studies were performed to examine how different light conditions can influence both visual and thermal appraisals. In both studies, participants were exposed to different light conditions and transitions in randomized order, two of which (warm, dim and cool, bright light) were shared between both studies. Ambient temperature was manipulated between these studies: the first was in a thermoneutral environment (Study 1; 21 °C) whereas the latter was performed in a mild cold environment (Study 2; 17 °C). The dependent variables included appraisals, mood, alertness, physiological arousal and thermoregulation. In this Windsor contribution, we investigate the shared within-subjects light manipulation in combination with the between temperature manipulation, and assess how these factors influence visual and thermal appraisals. Currently, the manuscript of Study 1 is under review, whereas the manuscript of Study 2 is being drafted.

2.1 Participants

In both studies, only healthy participants were recruited via the J.F. Schouten School for User-System Interaction Research database. The following inclusion criteria applied: no extreme chronotypes (only people in the range of 3.8 < Midsleep < 6.6 on the Munich Chronotype Questionnaire (Roenneberg, Wirz-Justice and Merrow, 2003), based on Zavada et al. (2005)), people using no medication other than the contraceptive pill, and no people who had travelled intercontinentally over the past three months. Participants were screened for this with an online questionnaire prior to the study. In total, we had 61 participants in the studies: 38 participants in Study 1, 23 in Study 2 (Table 1). The studies were approved by the Institutional Ethical Review Board. All participants gave their written informed consent and received monetary compensation for participation.

Table 1. Participants Characteristics



	Cold (n=23)	Neutral (n=38)	Overall (n=61)
Gender			
Female	13 (56.5%)	19 (50.0%)	32 (52.5%)
Male	10 (43.5%)	19 (50.0%)	29 (47.5%)
Age (in years)			
Mean (SD)	23 (± 2.0)	24 (± 2.9)	23 (± 2.6)
Range	18 to 26	20 to 31	18 to 31
Length (in meters)			
Mean (SD)	1.7 (± 0.13)	1.8 (± 0.098)	1.7 (± 0.11)
Range	1.4 to 2.0	1.6 to 2.1	1.4 to 2.1
Weight (in kg)			
Mean (SD)	64 (± 11)	69 (± 11)	67 (± 11)
Range	47 to 88	48 to 95	47 to 95
BMI			
Mean (SD)	22 (± 2.6)	22 (± 2.5)	22 (± 2.5)
Range	18 to 27	18 to 30	18 to 30

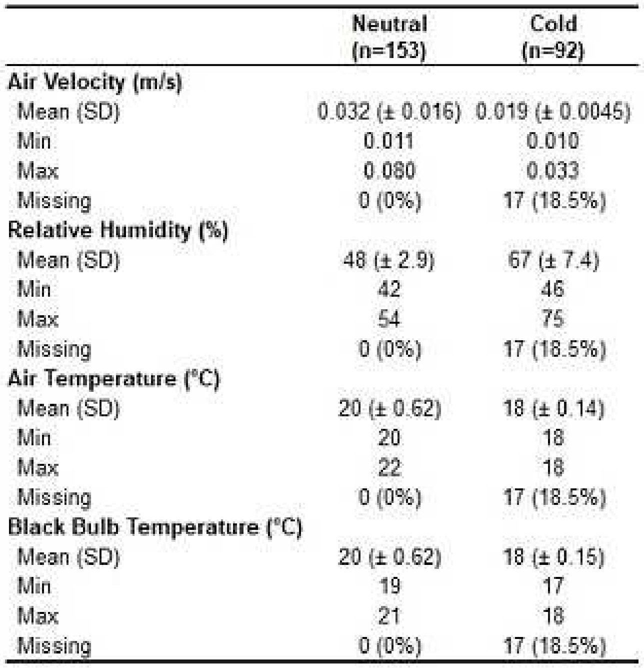
2.2 Setting

Both experiments were conducted in a climate chamber of 3.6x5.4x2.7m3 (WxLxH). Using a partitioning wall, this room was split to create two work spaces in the room. The reflectances of the various surfaces in the room were measured using a Minolta Luminance Meter LS-100. The walls of the climate chamber were off-white with a reflectance of 80.9%, whereas the white partitioning wall separating the two working areas had a reflectance of 91.8%. The grey floor had a reflectance of 27.7%, and the desk was light grey with a reflectance of 49.0%.

2.3 Stimuli

In Study 1, the indoor climate was kept constant at a neutral temperature of 21 °C, whereas in Study 2 the indoor climate was set to a mild cold temperature of 17 °C (Table 2). During the sessions, participants wore a standardized clothing set with an estimated clothing value of .7 clo, including insulation of the chair.

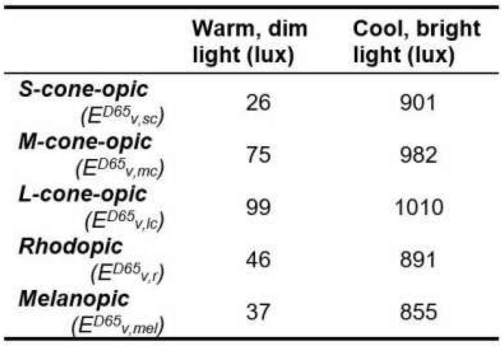
Table 2. Environmental Characteristics (averaged per session)



	Neutral (n=153)	Cold (n=92)
Air Velocity (m/s)		
Mean (SD)	0.032 (± 0.016)	0.019 (± 0.0045)
Min	0.011	0.010
Max	0.080	0.033
Missing	0 (0%)	17 (18.5%)
Relative Humidity (%)		
Mean (SD)	48 (± 2.9)	67 (± 7.4)
Min	42	46
Max	54	75
Missing	0 (0%)	17 (18.5%)
Air Temperature (°C)		
Mean (SD)	20 (± 0.62)	18 (± 0.14)
Min	20	18
Max	22	18
Missing	0 (0%)	17 (18.5%)
Black Bulb Temperature (°C)		
Mean (SD)	20 (± 0.62)	18 (± 0.15)
Min	19	17
Max	21	18
Missing	0 (0%)	17 (18.5%)

Two light settings were created using two sets of four ceiling-mounted luminaires (PowerBalance Tunable Whites; RC464B LED80S/TWH PSD W60L60), which were installed above each desk. The two lighting conditions purposefully differed substantially in both visual experience and melanopic activation. The warm, dim light condition had a CCT of 2708 K and 97 lux, and the cool, bright condition had a CCT of 5854 K and 1021 lux on the eye. Table 3 shows the α-opic equivalent daylight (D65) illuminances of the two light conditions. In Figure 1 the spectral power distribution of the light conditions is shown.

Table 3. Light Characteristics of the two conditions



	Warm, dim light (lux)	Cool, bright light (lux)
S-cone-opic ($E^{D65}_{v,sc}$)	26	901
M-cone-opic ($E^{D65}_{v,mc}$)	75	982
L-cone-opic ($E^{D65}_{v,lc}$)	99	1010
Rhodopic ($E^{D65}_{v,r}$)	46	891
Melanopic ($E^{D65}_{v,mel}$)	37	855

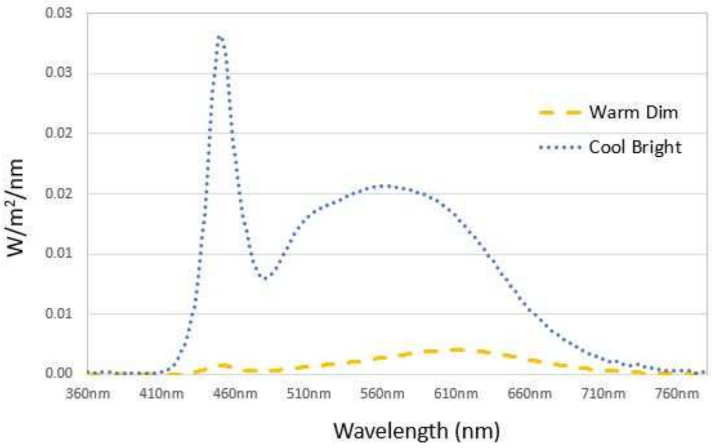


Figure 1. Spectral power distributions of the light conditions

2.4 Procedure

In both studies, participants attended four experimental sessions of 90 minutes each, at least one day apart. For the current analyses, only two of the lighting conditions were included (i.e., only the two conditions that were identical between both studies). The protocol of the two studies was highly similar, except for an additional cognitive task in Study 2.

At arrival, participants were guided to their desk in the climate chamber. In baseline lighting (warm, dim light), participants first completed an initial questionnaire, applied the sensors for the physiological measurements and practiced the task(s). After thirty minutes of adaptation to the environment, the measurements started. Physiological measures were taken continuously for an hour, whereas the questionnaire and task were completed every fifteen minutes (four times in total). Methods and results of the physiological measurements, task and non-comfort related self-reports are reported elsewhere. The first measurement block was a baseline measurement, after which the experimental phase of the study started, in either warm, dim or in cool, bright light. In this phase, participants completed three repeated measurement blocks, each fifteen minutes in duration, which were identical to the baseline measurement. Figure 2 shows a schematic representation of this procedure for one session.

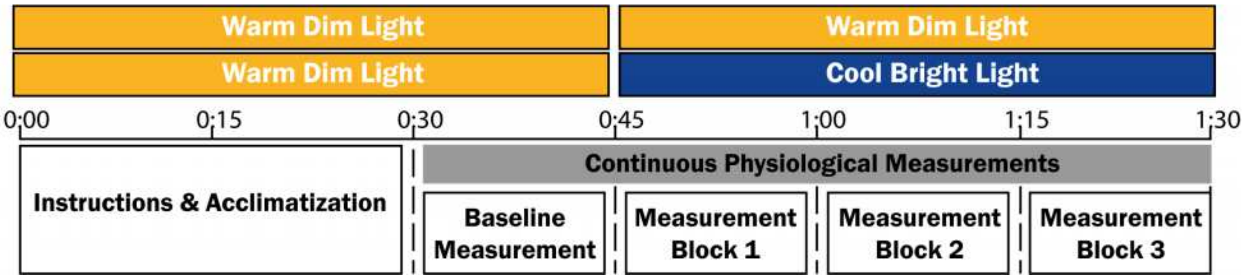


Figure 2. The timing of the light conditions in the procedural overview of one experimental session

2.5 Measurements

Thermal appraisals were evaluated using three items based on the ASHRAE standard 55 (ASHRAE, 2004). A discrete seven-point scale was used for thermal sensation (Sensation$_T$: from Cold (-3) to Hot (3)), a binary scale for the evaluation of thermal acceptance (Acceptance$_T$: Acceptable/Unacceptable), and one scale split in two 3-point parts for thermal comfort (Comfort$_T$): from Very Uncomfortable (-2) to Just Uncomfortable (0) and from Just Comfortable (1) to Very Comfortable (3)).

Visual appraisals were probed using five items that were aligned with the thermal comfort items. In the visual appraisals, a distinction was made for the perceived intensity and the perceived colour of the light. Therefore, the visual sensation of the lighting intensity (Sensation_{VI}) and experienced colour of the light (Sensation_{VC}) were evaluated separately using seven-point discrete scales (Sensation_{VI}: from Dim (-3) to Bright (3) and Sensation_{VC}: from Very Warm (-3) to Very Cool (3)). Again, a binary scale was used for visual acceptance of the lighting (Acceptance_{V}: Acceptable/Unacceptable). Visual comfort was evaluated using the same scales as for Comfort_{T}, although separately for the intensity and colour of the light. However, as they correlated highly and had a Cronbach's α of .86, they were averaged into one visual comfort measure: Comfort_{V}.

2.6 Statistical Analysis

After outlier and normality checks, analyses were done using mixed linear models with Participant and Session nested within Participant as Random Intercepts on the combined dataset of Study 1 and Study 2. The effect of Light Condition on sensation regarding the intensity and CCT of the light was tested separately to examine whether the manipulation had been visible. In this model, Light Condition was the only fixed effect that was included.

Additionally, mixed linear models with Participant and Session nested within Participant as Random Intercepts were run for Sensation_{T} and Comfort_{T}. In these models, Light Condition, Thermal Condition and the interaction between Light Condition and Thermal Condition were included as fixed effects to predict thermal perception. For post-hoc comparisons, Tukey's corrections were applied. Due to the skewed distribution of Acceptance_{T}, this variable was only visually inspected.

Last, to explore parallels in light-induced variations in visual comfort and thermal comfort as well as the relation between visual and thermal comfort, two multilevel models were run. Both included Participant and Session nested within Participant as Random Intercepts. The effect of Light Condition, Thermal Condition and the interaction between Light Condition and Thermal Condition (fixed effects) on Comfort_{V} (DV) was tested, as well as the relation between Comfort_{V} and Comfort_{T}.

All statistical analyses were performed using RStudio Version 1.1.463.

3. Results

3.1 Manipulation Check

Significant main effects of Light Condition on Sensation_{VI} and Sensation_{VC} were found in the expected direction. Participants perceived the warm, dim condition as significantly less bright (EMM= -0.5 ± SE = 0.1) compared to the cool, bright light (EMM = 1.6 ± SE = 0.1; t(1,59) = 18.4; p<.001). The sensation of the colour of the light in the warm, dim condition was warmer (EMM =0 .5 ± SE = 0.1) compared to the cool, bright light (EMM = -1.5 ± SE = 0.1; t(1,118) = -12.8; p<.001).

3.2 Main effect of light on thermal perception and interaction of light and temperature

Sensation$_T$ was significantly affected by the Thermal Condition only (Figure 3; t(1,103) = 2.6, p = 0.01). Thermal sensation was lower (EMM = -1.0 ± SE = 0.1) in the cold environment compared to the neutral environment (EMM = -0.6 ± SE = 0.1). There was no significant main effect of Light Condition (t(1,59) = 1.5, p=0.14) and no interaction effect between Light Condition and Thermal Condition (t(1,59) = -1.5, p=0.14).

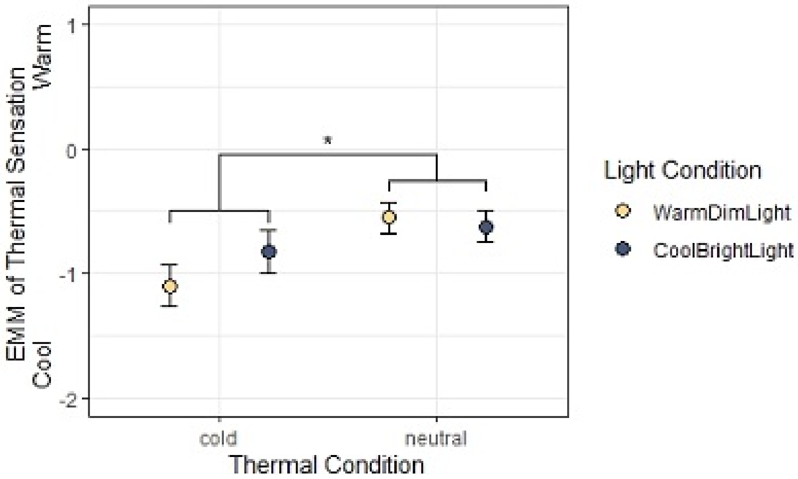


Figure 3. Main effect of temperature on thermal sensation. The error bars show the standard errors around the estimated marginal means of thermal sensation. *: p<0.05

Acceptance$_T$ was only visually inspected due to the skewed distribution. Overall, only 7.1% of the total occasions (n=365) were voted as unacceptable. In the warm, dim light in the cold environment, least participants evaluated the thermal environment as acceptable (78.3%). In the other conditions, thermal acceptance was always well above 90%.

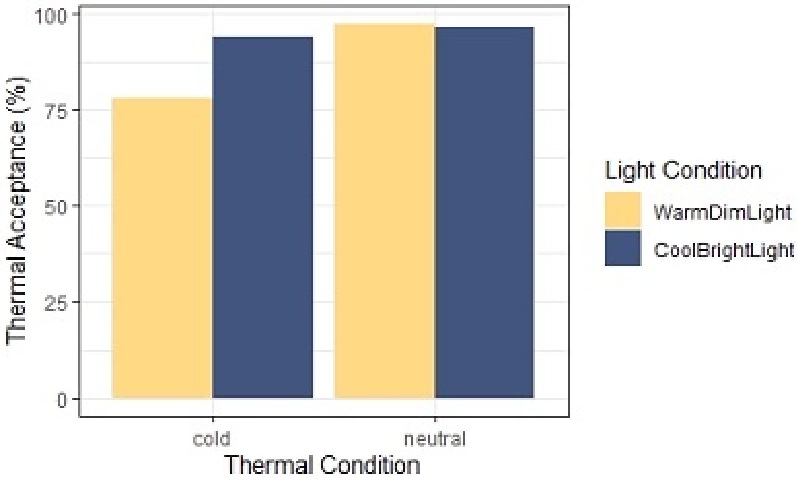


Figure 4. Percentages of the thermal acceptance votes

The temperature significantly affected Comfort$_T$ (t(1,107) = 3.4, p < .001). In the neutral environment, the average thermal comfort vote was 1.3 (EMM ± SE = 0.1), whereas – in line with the expectations – in the cold environment this was lower (EMM = 0.8 ± SE = 0.1). The effect of Light Condition and the interaction between the Light Condition and Thermal condition showed no statistically significant effects, but suggested non-significant trends with t(1,59) = 1.8 with p = 0.07 and t(1,59) = -1.7 with p = 0.09, respectively. Post-hoc comparisons with Tukey’s correction only demonstrated a significant effect of temperature in the warm, dim light condition (Figure 5; t(1,106) = -3.4, p = 0.01). In the cold environment with warm, dim lighting, thermal comfort votes were 0.6 (EMM ± SE = 0.2), whereas in the neutral environment the average thermal comfort vote in warm, dim light was 1.4 (EMM ± SE = 0.1). In the cool, bright light, there were no significant differences between the two Thermal Conditions (t(1,107) = -1.4, p = 0.50). There were also no significant differences in thermal comfort between the two lighting conditions in the neutral (t(1,59) = 0.5, p = 0.97) or the relatively cold environment (t(1,59) = -1.8, p = 0.26).

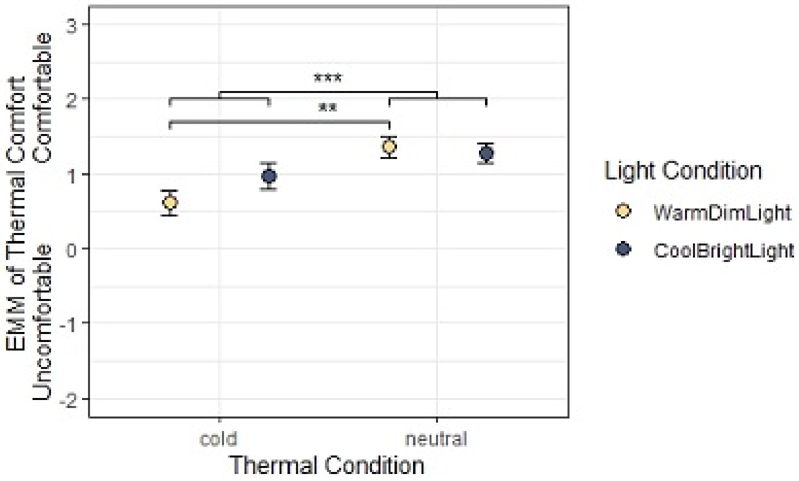


Figure 5. Interaction effect of light and temperature on thermal comfort. The error bars show the standard errors around the estimated marginal means of thermal comfort. **: p <0 .01, ***:

3.3 Exploring interrelationships between thermal and visual comfort

The effect of Thermal Condition and the interaction between the Light Condition and Thermal condition showed no statistically significant effects on Comfort$_V$ (t(1,118) = 1.1 with p = 0.28 and t(1,59) = -1.0 with p = 0.34, respectively). The main effect of Light Condition on Comfort$_V$ showed a non-significant trend (Figure 6: t(1,59) = -1.7, p = 0.09). Post-hoc comparisons with Tukey’s correction demonstrated that in the neutral thermal environment, participants evaluated the warm, dim light as more visually comfortable (EMM = 1.4 ± SE = 0.1) compared to the cool, bright light (EMM = 0.8 ± SE = 0.1). In the cold environment no such difference between the light conditions was significant (t(1,59) = 1.7, p = 0.32). In both the warm, dim light condition (t(1,117) = -1.1, p = 0.70) and the cool, bright light condition (t(1,117) = 0.2, p = 1.00) there were no differences in Comfort$_V$ between the two Thermal Conditions.

The relationship between $Comfort_V$ and $Comfort_T$ was significant ($p < 0.001$): a higher visual comfort vote was related to a higher thermal comfort vote ($\beta = 0.2 \pm SE = 0.1$).

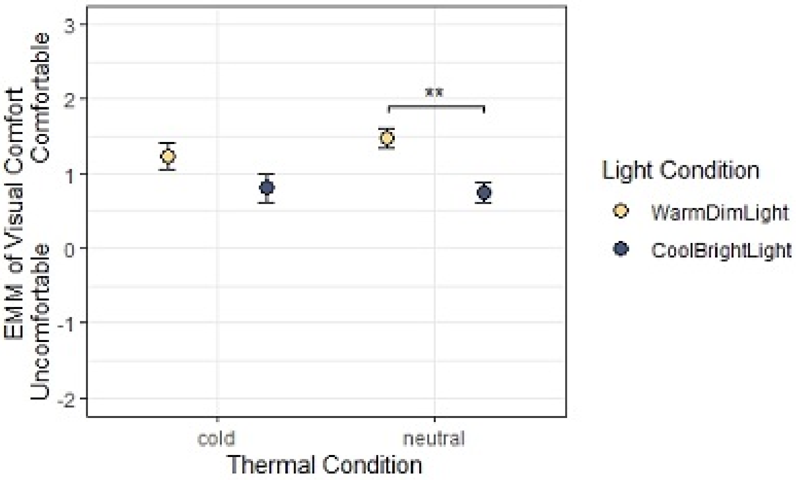


Figure 6. Effect of light and thermal condition on visual comfort. The error bars show the standard errors around the estimated marginal means of visual comfort. **: p <0.01

4. Discussion

In order to explore how light and temperature can be used to realize energy savings in buildings, we studied cross-modal effects of light and temperature. Additionally, interrelationships between visual and thermal perception were examined. In two separate studies, the effects of various light conditions on visual and thermal appraisals were tested. The first study was performed in a neutral environment and the second in a mild cold environment. In this Windsor contribution, the results of these studies were merged to examine the combined effects of light and temperature on visual and thermal appraisals.

Thermal comfort and sensation both were largely dependent on the ambient temperature. Participants perceived the cold environment as colder and more uncomfortable compared to the neutral environment. Similarly, the visual comfort and sensation were mainly influenced by the light conditions. In general, the warm, dim lighting was evaluated as warmer and dimmer compared to the cool, bright lighting. In addition to those findings, the current study demonstrated a significant relationship between visual and thermal comfort. The positive but small β-estimate indicates that when visual comfort increases, thermal comfort increases slightly as well. These findings are in line with the results found by te Kulve et al. (2018) who performed a similar analysis on several studies. In these studies, temperature was manipulated within participants, whereas light was manipulated both within and between the participants. Any potential directionality or causality in this relationship is difficult to demonstrate. A potential explanation of the relationship might be the central regulation of comfort in the insula of the brain (Frackowiak, 2004). The insula processes the influence of peripheral cues and translates these to consciously experienced emotional states. This physical proximity of the two concepts in processing in the brain may result in the relationship as was found in the current study. Discomfort concerning either the visual or the thermal environment may therefore lead to perceived discomfort of the other modality. This central regulation of comfort might also result in the inability of human beings to specify correctly and completely where the general feeling of discomfort that they experience originates from, which could lead to an overlap in thermal and visual comfort responses.

In addition to the relationship between thermal and visual comfort, some cross-modal effects emerged. The effect of light on visual comfort was only visible in the neutral, relatively comfortable, condition. In the cold environment, the effect of the light conditions on visual comfort was attenuated. Furthermore, thermal comfort only differed between the two ambient temperatures in warm, dim light. However, this difference in thermal comfort due to different ambient temperatures was not present in cool, bright light. As suggested by Chinazzo et al. (2018), this might be explained by the thermal expectation of the occupant, which influences the occupants' comfort. They suggested that the quantity of light could potentially affect people's thermal comfort. In the current study, not the quantity, but the colour of the light might have induced a thermal expectation of a certain type of environment. In the cool, bright light condition, participants may have had the expectation of a cool environment. When this expectation was met by the mild cold ambient temperature, participants thermal comfort changed.

Interestingly, in the current study no effects of intensity and CCT interventions on thermal sensation were found. The psychological association of bright light with sun light and therefore warmth (Xu and Labroo, 2014) was not confirmed by this study. This might be explained by the employed conditions. In this study, we contrasted warm, dim light with cool, bright light which both do not evoke the psychological association with sunlight and therefore warmth. Additionally, the current study could not provide evidence for the existence of the hue-heat hypothesis (Candas and Dufour, 2005). Variations in CCT of light might not be strong enough to influence participants' belief of the temperature. Possibly, only saturated colours are able to actually evoke differences in thermal sensation (Winzen, Albers and Marggraf-Micheel, 2014; Ziat et al., 2016). Additionally, the intensity and correlated temperature effects may have cancelled each other out based on the combination of the association between bright light and warmth and the hue-heat hypothesis.

The main finding of the current study is the significant relationship between visual and thermal comfort, which would plead for a holistic approach when studying any comfort related question. Whenever one aspect in the environment leads to discomfort, this is likely to influence the comfort experience of any other aspect. Using less heating and/or cooling in an office building to save energy should therefore be applied vary carefully as this may render thermal discomfort and thereby influence the general comfort experience.

This study also had some limitations that need to be taken into account when interpreting the results. Both studies were conducted in the rather clinical setting of a climate chamber without daylight access. If comfort is a holistic experience, it may well be that participants' comfort was greatly influenced by this setting. Field studies could be done to test whether there is a relationship between thermal and visual comfort in real life. Additionally, the temperature manipulation turned out to be smaller than expected due to the temperature of the outdoor air that was used to heat, cool and ventilate the room. In Study 1 in winter, it was hard to heat the room up to the target temperature of 21 °C, whereas in summer the climate chamber could not be cooled down to 17 °C. Despite the relatively small difference in ambient temperature, the seasonal thermal adaptation is expected to have increased the perceived ambient temperature as, generally, people prefer slightly higher temperatures when it is warmer outside compared to when it is colder outside (Hoof, 2010). Additionally, the temperature manipulation coincided with seasonality, which may have influence the results based on the study by Chinazzo et al. (2018).

Future research could specifically focus on determining any potential causality in the relationship between thermal and visual comfort. Additionally, thermal effects of light intensity and correlated colour temperature should be disentangled in order to confirm which psychological association, the hue-heat hypothesis or the association of bright light with warmth, is causing these cross-modal effects. Finally, in the current study warm, dim lighting was used as a baseline light condition, which resulted in a transition before the cool, bright light condition, in contrast to no transition in the warm, dim light condition. Future studies could examine whether such a transition can lead to changed sensation independently of the light condition that is being transitioned to.

From this study, we can conclude that visual and thermal comfort are closely related. However, whether thermal comfort can be influenced by light, or visual comfort by ambient temperature, is a complicated question. There could be multiple mechanisms at play, such as the hue-heat hypothesis or an association of bright light with warmth. The interrelationships between visual and thermal comfort are expected to be caused by the central regulation of comfort in the brain mainly. These findings could be applied in office environments to save energy by controlling the temperature less strictly and compensating potential discomfort with visually comfortable light settings.

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