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Correlated colour temperature of morning light influences alertness and body temperature

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ABSTRACT

Though several studies have reported human alertness to be affected by the intensity and spectral composition of ambient light, the mechanism behind this effect is still largely unclear, especially for daytime exposure. Alerting effects of nocturnal light exposure are correlated with melatonin suppression, but melatonin levels are generally low during the day. The aim of this study was to explore the alerting effect of light in the morning for different correlated colour temperature (CCT) values, as well as its interaction with ambient temperature. Body temperature and perceived comfort were included in the study as possible mediating factors. In a randomized crossover design, 16 healthy females participated in two sessions, once under 2700 K and once under 6500 K light (both 55 lx). Each session consisted of a baseline, a cool, a neutral and a warm thermal environment. Alertness as measured in a reaction time task was lower for the 6500 K exposure, while subjective sleepiness was not affected by CCT. Also, core body temperature was higher under 6500 K. Skin temperature parameters and perceived comfort were positively correlated with subjective sleepiness. Reaction time correlated with heat loss, but this association did not explain why the reaction time was improved for 2700 K.

1. Introduction

Human sleepiness and alertness are influenced by environmental light exposure. Several studies have reported that bright light reduces subjective sleepiness both during night and daytime (see [1,2] for reviews). However, not only light intensity, but also its spectral composition may affect sleepiness, though conflicting results have been published [3–6]. Several studies have revealed that exposure to monochromatic blue light of 460 nm during the biological night results in lower subjective sleepiness and shorter reaction times in vigilance tasks compared to green light of 555 nm [4,7]. Revell et al. reported that morning alertness also depends on spectral composition [8]. In their study, subjective alertness levels were found to be higher under exposure to relatively short wavelengths.

At night, alerting effects of light are usually correlated with suppression of the hormone melatonin by light [1,9]. Melatonin suppression is thought to largely depend on stimulation of the so-called intrinsically photosensitive retinal ganglion cells (ipRGC's), which are most sensitive to light in the blue part of the spectrum (peak sensitivity around 480 nm) [7,10]. Exposure to light with a higher correlated

colour temperature (CCT) (having a higher energy content between 450 and 500 nm) also results in lower melatonin concentrations [11]. Since melatonin is generally only present at night, this cannot be the sole reason why light has alerting effects, especially so during daytime. One hypothesis is that daytime blue rich light entrains the circadian rhythm, thereby positively influencing daytime alertness in a more indirect way. This was confirmed by a 4 week intervention study by Viola et al. [12]. However, this does not explain the acute effects of light on alertness. Moreover, these effects are not always clear-cut. Shamsul et al. observed that self-assessed sleepiness was lowest at 6500 K exposure (compared to 3000 K and 4000 K), while typing speed peaked at 4000 K [13]. Mixed effects were also reported by Smolders and de Kort: 6000 K improved subjective vitality while 2700 K showed subtle performance improvements during addition and letter cancellation tasks [14]. Santhi et al. concluded that blue enriched light was not very effective in counteracting sleep inertia [15]. Finally, daytime blue monochromatic light exposure resulted in improved auditory PVT reaction times compared to green light [5], while opposite effects were observed in another study [6].

Presently, it is unclear why some studies have found alerting effects

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of light with higher energy in the short wavelength range (450–500 nm), while others have not [2]. One aspect that merits more attention is the effect that light exposure has on thermophysiological processes. It is known that thermophysiology strongly influences sleepiness and alertness [16]. For instance, a lower core body temperature (CBT), high distal skin temperatures and distal-proximal skin temperature gradient (DPG) have been associated with a higher sense of sleepiness [17,18]. Of course, ambient temperature is the strongest environmental factor that influences body temperatures. Interestingly, light (intensity and CCT) may also affect CBT [19,20]. For example, if CBT may be increased by blue light, it might thereby enhance alertness. Along very different lines, alertness might also be influenced by subjective judgements such as perceived comfort and perception of the indoor environment [21,22]. These subjective parameters are also affected by light and ambient temperature. In conclusion, body temperature and perceived comfort may be mediating factors in alerting effects of light.

The aim of this study is to explore the alerting effects of exposure to light with different CCTs during morning hours for different ambient temperatures. The research questions of this study are illustrated in a conceptual model (Fig. 1), showing light and ambient temperature as the main factors affecting alertness. Body temperature and perceived comfort are mediating factors. These factors in turn are influenced by CCT and ambient temperature.

2. Method

The study compromised a randomized crossover protocol with two laboratory sessions per participant. The Medical Ethical Committee of Maastricht University Medical Centre + approved the study protocol. All participants provided a written informed consent previous to the experiment. All procedures were conducted in accordance with the Declaration of Helsinki. Experiments took place between August 2015 and January 2016.

2.1. Participants

All 16 participants were recruited by advertisements on local billboards at the university and at the website digi-prik.nl. All participants met the following inclusion criteria: Caucasian females, generally healthy, age 18 to 30 years, BMI 18–25 kg/m², using contraceptives “microgynon 30” or “levonorgestrel/ethinyl estradiol” and a normal chronotype (midsleep time between 3.5 and 5.0 AM (local time), mean for workday and free days) [23] (see Table 1 for descriptive data). Exclusion criteria consisted of: colour blindness, ocular pathologies, medication use, pregnancy, hypertension, general feeling of illness at day of experiment, (history of) cardiovascular diseases, contra-indication of the telemetric pill. A medical questionnaire and a chronotype questionnaire [24] were used to check whether participants met the inclusion and exclusion criteria.

Fig. 1. Conceptual model of the relations between light exposure, ambient temperature, alertness, body temperature and perceived comfort. The main factors are indicated with solid arrows and the mediating factors with dashed arrows. The arrows are clarified in the introductory of the results section.

Table 1
Characteristics of the 16 female participants.

Characteristic	Average (± SD)
Age (yr)	22.2 ± 2.37
Body mass (kg)	62.4 ± 5.33
Height (m)	1.70 ± 0.06
BMI (kg/m ²)	21.5 ± 2.07
Body fat (%)	27.9 ± 4.72
Midsleep time (h:min ± min)	4:10 ± 34

Fig. 2. Scheme of the light and temperature conditions during the experiments. * The order of the sessions was randomized across participants; half of them started with the 2700 K session and the others with the 6500 K session. ** The order of the cool and warm conditions was randomized among participants, but was the same within one participants' two sessions.

2.2. Protocol

During both sessions of the crossover study, the participants were exposed to light with an illuminance of 55 lx at the eye in the direction of view. In one session the light had a CCT of 2700 K and in the other session the CCT was 6500 K (Fig. 2). Apart from the light exposure, both sessions were identical. Time between the two sessions was at least 1 week with a maximum of up to 3 weeks.

The participants arrived at the laboratory at 9:00 PM. They refrained from food, caffeine and alcoholic consumption starting 12 h before the experiment began the next morning. After arrival in the evening, the questionnaires and the tests were practiced. The participants were allowed to sleep from 11:00 PM till 7:00 AM the next morning (light was switched off (< 1 lx) and the indoor temperature was 21 °C). After the participants woke up, they got a small standardized breakfast (53 kcal). After that, all preparations (including the insertion of the intravenous cannula) took place under dim light conditions (5 lx). At 7:45 AM, each session started with a 45-min baseline period at a thermoneutral temperature (29 °C) under dim light (illuminance at the eye position in the direction of view: 5 lx, 4000 K). The baseline was followed by three test blocks with each a different ambient temperature: a cool temperature condition (26 °C), a thermoneutral condition (29 °C) and a warm condition (32 °C). Each block lasted 75 min. The two CCTs were tested in separate sessions and the order of these sessions was randomized across participants. The order of the cool and warm ambient temperature conditions was also balanced; half the participants started with the warmer condition in block 1, and the other half started with the cool condition. However, between the two CCT sessions of one participant, the order of the cool and warm temperatures was kept identical. For each participant, the second block

Fig. 3. Procedure during each measurement block (75 min). Measurements indicated in this figure are core body temperature (CBT), Skin temperature (Skin temp), Heart rate (HR), Energy expenditure (EE), Laser Doppler Flowmetry (LDF), Blood pressure (BP), Questionnaires (Q), Alertness task (PVT) and drawing blood from the catheter (blood). The intervals (int.) A & B used for the analyses are indicated (Section 2.4).

contained the thermoneutral condition to ensure that the temperature change between different exposures was the same for each participant. During each condition, the participant was lying in semi-supine position on a stretcher and was dressed in underwear (clothing insulation value of 0.04 clo, see [25]). Skin temperatures (SKT), core body temperature (CBT), heart rate, energy expenditure and skin blood flow (SBF) of the hand and underarm were measured continuously on a 1-minute interval. Blood pressure was measured every 30 min (at $t = 10$, $t = 40$ and $t = 70$). Every 15 min participants filled out a questionnaire including comfort ratings and subjective sleepiness (see below). After 55 min light and temperature exposure, the participant performed an 8-minute auditory Psychomotor Vigilance Task (PVT). After the PVT, blood was drawn from the venous catheter. Before switching to the next temperature exposure, there was a 15-minute break during which the participant received a standardized snack (53 kcal) and was allowed to drink water (Fig. 3).

2.3. Measurements

2.3.1. Indoor environment

Air temperature and relative humidity were measured at one-minute intervals by means of four dataloggers (iButton, DS1923, Maxim). The iButtons were placed next to the participant at a height of 0.1 m, 0.3 m, 0.6 m and 1.1 m. The installed light system was a LED wall washer (Philips SkyRibbon IntelliHue Wall Washing Powercore). The illuminance of the lighting was confirmed with a lux meter (Testo 545) each time the lighting condition changed. The illuminance was measured in the outward direction of the optical axis at the outer surface of the participant's eye in its most usual viewing direction. The spectrum of each lighting condition was measured once using a radio spectrometer (Jeti).

2.3.2. Alertness

As measures for alertness we used subjective sleepiness and PVT reaction times. Subjective sleepiness was assessed using the Karolinska Sleepiness Scale (KSS) ranging from 1 being “very alert” till 9 being “very sleepy and hard to keep awake” [26]. In the auditory PVT, which lasted 8 min, participants responded as fast as possible to an auditory stimulus by pressing the space bar of the keyboard [27,28]. The inter-stimulus interval at each trial was randomly drawn from a uniform distribution between 2 and 10s. The average PVT reaction time, best 10% and worst 10% were used for the analyses.

2.3.3. Body temperatures and cardiovascular parameters

Skin temperatures were measured by iButton dataloggers (DS1922L, Maxim) [29]. They were attached to 26 body sites as reported in a previous study [30]. Mean skin temperature (T_{meanskin}) was calculated using skin temperatures measured at the 14 ISO-defined skin sites [31]. Core body temperature was measured using a telemetric temperature pill (VitalSense® medical grade capsules, Equivital™, Hidalgo Limited). The pill was ingested in the evening before the experiment to ensure that it was sufficiently deep in the intestinal track. The Sensory Electronics Module of the Equivital EQ02 Life Monitor system

(Equivital™, Hidalgo Limited UK) measured heart rate continuously during the experiments. Blood pressure was measured with an ambulatory device (upper arm blood pressure monitor MTP, Medisana®).

2.3.4. Skin blood perfusion

Cutaneous blood flow was recorded using Laser Doppler Flowmetry (PF4000 & PF5000, Perimed AB, Sweden). Sensors were placed at the hand and underarm of the non-dominant arm. The measurements were performed with a standard probe (Probe 408, Perimed AB). Probes were placed in a probe holder (PH 08-1, Perimed AB) and mounted with double-sided adhesive tape. Laser Doppler Flowmetry does not provide absolute measurements of blood flow. Therefore, the individual perfusion responses were normalized by individual baseline values (interval 10–35 min).

2.3.5. Energy expenditure

Human energy expenditure was measured using indirect calorimetry. Oxygen consumption and carbon dioxide production were measured with an automated respiratory gas analyser and a mask (Omnicol Indirect Calorimeter, Maastricht Instruments). Samples were taken every breath and averaged over 1-minute intervals. Gas analysers and flow meter were calibrated previously to all measurements. Energy expenditure was calculated from the data according to Weir's method [32].

2.3.6. Blood parameters

Blood was collected via a venous catheter in an antecubital vein. The catheter was placed at least 15 min before the baseline measurement. During every blood drawing procedure, a total of 40 ml was taken. Blood was drawn after 40 min during baseline and after 70 min since the start of each block. Cortisol levels were measured for all conditions (using Electro Chemi Luminescence Immuno Assay (ECLIA)). Baseline melatonin levels were determined (Melatonin direct Serum/Plasma/Saliva RIA, IBL international) to verify whether the levels were indeed low (as expected) at the onset of both experimental light conditions.

2.3.7. Perceived comfort

Thermal comfort and thermal sensation were self-reported using visual analogue scales (VAS) [25,33]. The perception of the light in the room was also self-reported using two VAS. The first ranged from “very dim” to “very bright” and the second from “very cool colour” to “very warm colour”. Subsequently, after these two questions, participants were asked to indicate how comfortable the lighting was, ranging from “very uncomfortable” to “very comfortable”. Valence and arousal were evaluated using the 9-points self-assessment mannequin [34]. All subjective parameters were included in the questionnaire that was filled out every 15 min.

2.3.8. Sleep characteristics

The sleep characteristics of each participant were measured via a sleep diary (during 1 week prior to the experiments) and via actigraphy (using a Actiwatch Spectrum, Philips Respironics) during the night

Table 2
Sleep characteristics of the participants.

	Actiwatch (night at laboratory)		Sleep diary (week prior to experiment)		
	Sleep duration [h:min ± min]	Awake [%]	Bedtime [h:min ± min]	Wakeup time [h:min ± min]	Sleep duration [h:min ± min]
CCT “2700 K”	7:17 ± 41	14 ± 7.9	23:26 ± 25	7:56 ± 33	7:35 ± 29
CCT “6500 K”	7:23 ± 37	13 ± 7.2	23:20 ± 28	7:46 ± 38	7:41 ± 28
Significance	p = 0.326	p = 0.249	p = 0.164	p = 0.197	p = 0.455

before the experiment. The sleep diary consisted of an evening questionnaire about activities and sleepiness during the day and a morning questionnaire about sleep timing and sleep quality. The average time participants went to bed, woke up and the sleep duration in the week prior to the experiment was calculated for each participant (Table 2). During the night at the laboratory, participants wore an Actiwatch Spectrum (Philips Respironics) to measure sleep. The total sleep duration as well as the percentage of time awake were calculated from the Actiwatch data (Table 2).

2.4. Data analyses & statistics

For each session, the average indoor temperature and relative humidity (RH) per temperature condition was calculated over the 0–75 min intervals. Paired sample *t*-tests were used to check that there were no temperature or RH differences between the light sessions (Section 3.1).

For the analysis of body temperatures, the average of interval $t = 50 - t = 55$ min (Interval A, Fig. 3) was used to ensure maximal effect of the light exposure without possible disturbances of the PVT that started at 55 min. Physiological data (Energy expenditure, heart rate, SBF) were averaged from 20 to 55 min interval (Interval B, Fig. 3). The same interval was used for the questionnaires, including the 2nd, 3rd and 4th questionnaire of each condition (see Fig. 3). For blood pressure, the average over the 3 measurements at 10, 40 and 70 min was determined.

A random intercept linear mixed model was applied to test the effects of CCT and ambient temperature (Eq. (1)). Dependent variables (*y*) were: subjective sleepiness, PVT reaction time, thermophysiological parameters and perceived comfort parameters. Independent variables were: CCT exposure (Light_{6500K}, with the 2700 K condition as reference), temperature condition (Temp_{warm} and Temp_{cool} with the neutral condition as reference) and timing of the block (block_{NR1} and block_{NR3}, with the second block as reference). The interactions between the CCT exposure and the temperature conditions and the interactions between the CCT exposure and the time of the block were also included in the model (Eq. (1)). The dependent variable is represented by y_{ij} for the i^{th} participant during block j . The intercept is represented by a_0 . The random intercept (G_{0i}) was applied to take into account individual variations between the participants. Backward selection was used to determine inclusion of the independent variables. In case the *p*-value of the interaction between light and temperature condition, or the interaction between block number and light session was < 0.10, post hoc analyses per temperature condition or block number were carried out. The Benjamini Hochberg (BH) procedure was performed to control for the false discovery rate (FDR) by multiple testing [35]. The procedure was carried out on the effect of light session and the “BH *p*-value” (p_{BH}) was reported for uncorrected *p*-values < 0.05 (Section 3.2 and 3.3).

$$\begin{aligned}
 y_{ij} = & a_0 + \beta_1 \text{Light}_{6500\text{K}} + \beta_2 \text{Temp}_{\text{cool}} + \beta_3 \text{Temp}_{\text{warm}} + \beta_4 \text{Block}_{\text{NR1}} \\
 & + \beta_5 \text{Block}_{\text{NR3}} + [\beta_6 \text{Temp}_{\text{cool}} * \text{Light}_{6500\text{K}}] + [\beta_7 \text{Temp}_{\text{warm}} \\
 & * \text{Light}_{6500\text{K}}] + [\beta_8 \text{Block}_{\text{NR1}} * \text{Light}_{6500\text{K}}] + [\beta_9 \text{Block}_{\text{NR3}} * \text{Light}_{6500\text{K}}] \\
 & + G_{0i} + R_{ij}
 \end{aligned} \quad (1)$$

To test how much of the variance in the subjective sleepiness and

reaction time (dependent variables) was explained by the possible mediating factors (Fig. 1, arrows G and H), two linear mixed models were constructed for each dependent variable. In the first model the thermophysiological parameters were included as independent variables and in the second model the perceived comfort parameters were included.

Independent variables of the first model were the CBT, skin temperature, the skin blood flow at the underarm (SBF_{underarm}), the skin blood flow at the hand (SBF_{hand}) and heart rate. Because of the high interdependency between the various skin temperatures, only one skin temperature was included in the model. The model was therefore composed with sequentially the Tmeanskin, proximal skin temperature (Tproximal), distal skin temperature (Tdistal) and the distal proximal skin temperature gradient (DPG). The skin temperature parameter that resulted in the best fit was used for the linear mixed model.

For the second model, independent variables linked to perceived comfort were: thermal comfort, thermal sensation, visual comfort, perceived light intensity, perceived light colour, valence and arousal. Backward selection was used to analyse the required parameters. The explained variances (R^2) of the mixed models were calculated according to the paper of Nakagawa and Schielzeth [36]. The marginal R^2 (R^2_{Marginal}) represents the explained variance by the fixed factors and the conditional R^2 ($R^2_{\text{Conditional}}$) represents the explained variance by both the fixed and random factors. Finally, in both models, CCT was added to the model with the best fit, to test if it significantly increased the proportion of variance explained on top of the other independent variables in the model (Section 3.4 and 3.5).

Statistical analyses were performed using IBM SPSS Statistics 22 for Mac. R-studio Version 1.0.143 was used for the variance analyses.

3. Results

Below, the results of the study are reported using the structure of the model in Fig. 1. First, Section 3.1 describes the light and temperature conditions. Subsequently the effects of the CCT of light on alertness, body temperature and perceived comfort are reported in Section 3.2 (see Fig. 1, arrows A–C). The effects of ambient temperature on alertness, body temperature and perceived comfort are described in Section 3.3 (Fig. 1, arrows D–F). The relation between body temperature and alertness (Fig. 1, arrow G), has been divided into effects on subjective sleepiness (Section 3.4) and PVT reaction time (Section 3.5). Also, the relationship between perceived comfort and alertness (Fig. 1, arrow H), has been divided into effects on subjective sleepiness (Section 3.4) and PVT reaction time (Section 3.5).

3.1. Indoor environmental conditions

As intended, ambient temperature and RH were not significantly different between the two CCT sessions (Table 3). The illuminance in the direction of view of the participant was 4.1 lx during the baseline period and the CCT set at 4000 K. During the 2700 K sessions the mean illuminance in the viewing direction of the participant equalled 54.4 lx, while during the 6500 K setting it was 55.4 lx (Table 4 and Fig. 4).

Table 3Measured ambient temperature and relative humidity (RH); average over entire condition duration (Mean $\pm$ Sd across participants).

	Light-session	Baseline	Mild cold	Thermoneutral	Mild warm
Temp [°C]	2700 K	28.1 $\pm$ 0.26	24.5 $\pm$ 0.45	28.1 $\pm$ 0.26	31.4 $\pm$ 0.68
	6500 K	28.2 $\pm$ 0.31	24.4 $\pm$ 0.37	28.2 $\pm$ 0.35	31.4 $\pm$ 0.56
	t-test p value	p = 0.478	p = 0.231	p = 0.264	p = 0.909
RH [%]	2700 K	37 $\pm$ 8.2	41 $\pm$ 7.3	36 $\pm$ 7.7	34 $\pm$ 6.0
	6500 K	38 $\pm$ 7.4	43 $\pm$ 6.6	37 $\pm$ 6.8	36 $\pm$ 5.1
	t-test p value	p = 0.806	p = 0.376	p = 0.645	p = 0.307

Table 4

Photopic illuminance and the corresponding human retinal photoreceptor weighted “alpha-opic” (equivalent) illuminances calculated according to [37].

	$I_{\max}$	2700 K	6500 K	Baseline
Photopic	555.0	54.36	55.36	4.13
“Cyanopic-lux”	419.0	13.46	46.39	1.77
“Melanopic-lux”	480.0	25.53	60.45	2.90
“Rhodopic-lux”	496.3	31.89	59.43	3.24
“Chloropic-lux”	530.8	43.24	56.32	3.66
“Erythropic-lux”	558.4	54.47	54.72	4.07
CCT [K]		2549	5831	3517

Fig. 4. Spectrum of the LED room lighting with a correlated colour temperature (CCT) of 2700 K and 6500 K measured at a photopic illuminance of approximately 55 lx.

3.2. Effect of CCT on alertness and thermophysiology

CCT had no significant effect on subjective sleepiness ($\beta = -0.18$, $p = 0.355$) (Fig. 5A). The average reaction time in the PVT task was shorter ($\beta = 0.014$ s, $p = 0.015$) during the 2700 K exposures as compared to 6500 K (Fig. 5A). Post hoc analyses showed that the average reaction time was significantly shorter in the 2700 K versus the

6500 K sessions during the 1st ($\beta = 0.023$ s, $p = 0.025$) and 2nd block ($\beta = 0.022$ s, $p = 0.019$), but not during the 3rd block ($\beta = -0.002$ s, $p = 0.874$) (Fig. 5B).

Interestingly, CBT was higher during 6500 K as compared to 2700 K ($\beta = 0.04$ °C, $p = 0.034$) (Fig. 6). During the cool condition, Tproximal was also higher for the 6500 K exposures ($\beta = 0.21$ °C, $p = 0.031$). This was not the case for the neutral and warm conditions. However, these effects were not significant after BH correction ($p_{BH} > 0.10$). Tmeanskin, Tdistal, the DPG and skin blood perfusion were not significantly affected by the CCT exposure (Table 5). Energy expenditure, heart rate and blood pressure were also not differently affected (Appendix A: Table A.1).

Baseline plasma melatonin was not significantly different ($p = 0.581$) at the end of the baseline before the 2700 K (40.8 pg/ml) and 6500 K (39.6 pg/ml) exposure. The change in plasma cortisol levels from baseline till the end of the light exposure was not different between the two CCT exposures ($\beta = 0.02$ μmol/l, $p = 0.540$). Time of the blocks had a significant effect ($p < 0.001$): cortisol levels were highest during the 1st block (0.62 μmol/l) and lowest during the 3rd block (0.42 μmol/l) (see Appendix A: Table A.2 for an overview).

Visual comfort was higher during 2700 K sessions as compared to the 6500 K sessions ($\beta = -0.28$, $p < 0.001$). Also, as expected, the colour of light was rated warmer during the 2700 K exposures ($\beta = -0.94$, $p < 0.001$). The CCT had no effect on thermal sensation ($p = 0.980$) or thermal comfort ($p = 0.542$).

To summarize the main effects of CCT: PVT reaction times were shorter during the 2700 K light exposures, but there was no effect of CCT on subjective sleepiness (Fig. 1, arrow A). Visual comfort regarding the tone of the light was higher during the 2700 K light exposures as compared to 6500 K (Fig. 1, arrow C). A CCT of 6500 K compared to 2700 K revealed significantly higher CBT and also high Tproximal (the latter during cool conditions only). No CCT effects were found on the other skin temperature parameters, physiological parameters or hormones (Fig. 1, arrow B).

Fig. 5. A) Subjective sleepiness and PVT reaction times (mean $\pm$ SEM) per combination of ambient room temperature and CCT; B) PVT reaction time for the two CCT conditions in all three test blocks, # $p < 0.10$, * $p < 0.05$ and ** $p < 0.01$.

Fig. 6. Core body temperature (5-min means $\pm$ SEM) during the 2700 K and the 6500 K exposures for the 1st (warm/cool condition), 2nd (neutral condition) and 3rd (warm/cool condition) block. The CBT during the 6500 K was significantly higher compared to the 2700 K sessions ($p < 0.05$).

Table 5

Average $\pm$ sd of the body temperature parameters per CCT, ambient temperature condition and block number (The thermoneutral condition always was during the 2nd block). In case the interaction between CCT and temperature/block was not significant, the mean of both CCT exposures was reported per temperature/block. Dependent parameters: Core body temperature (CBT), Mean skin temperature (Mean SKT), Proximal skin temperature (Prox SKT), Distal skin temperature (Distal SKT) and Distal Proximal skin temperature gradient (DPG), Skin blood flow (SBF). * $p < 0.05$ and ** $p < 0.01$. For the $p < 0.05$, the p_{BH} is reported.

Parameter	Session	Baseline	CCT exposure	Temperature			Time	
				Cool	Thermoneutral/2nd block	Warm	1st block	3rd block
CBT [°C]	2700 K	37.2 $\pm$ 0.17	37.2 $\pm$ 0.18	37.3 $\pm$ 0.16	37.2 $\pm$ 0.17	37.2 $\pm$ 0.17	37.2 $\pm$ 0.16	37.3 $\pm$ 0.17
	6500 K	37.2 $\pm$ 0.18	37.3 $\pm$ 0.16					
		$p = 0.253$	$p = 0.034$	Cool > neutral**, cool > warm**, neutral $\approx$ warm ns			1st < 3rd **	
			$p_{BH} = 0.153$					
Mean SKT [°C]	2700 K	34.2 $\pm$ 0.30	34.0 $\pm$ 1.31	32.5 $\pm$ 0.38	34.3 $\pm$ 0.64	35.4 $\pm$ 0.41	34.1 $\pm$ 1.58	33.8 $\pm$ 1.41
	6500 K	34.1 $\pm$ 0.26	34.1 $\pm$ 1.26					
		$p = 0.487$	$p = 0.556$	Cool < neutral**, cool < warm**, neutral < warm**			1st > 3rd **	
Prox SKT [°C]	2700 K	34.7 $\pm$ 0.37	34.7 $\pm$ 1.17	33.3 $\pm$ 0.38	34.9 $\pm$ 0.55	35.8 $\pm$ 0.48	34.6 $\pm$ 1.39	34.5 $\pm$ 1.24
	6500 K	34.6 $\pm$ 0.35	34.7 $\pm$ 1.06	33.5 $\pm$ 0.47	34.8 $\pm$ 0.50	35.8 $\pm$ 0.38		
		$p = 0.654$	cool: $p = 0.031$	Cool < neutral**, cool < warm**, neutral < warm**			1st $\approx$ 3rd ns	
			$p_{BH} = 0.153$					
			neutral: $p = 0.52$					
			warm: $p = 0.97$					
Distal SKT [°C]	2700 K	33.4 $\pm$ 0.84	32.3 $\pm$ 2.25	30.0 $\pm$ 1.02	32.5 $\pm$ 1.72	34.3 $\pm$ 1.25	32.8 $\pm$ 2.42	31.6 $\pm$ 2.28
	6500 K	33.1 $\pm$ 1.06	32.3 $\pm$ 2.17					
		$p = 0.193$	$p = 0.758$	Cool < neutral**, cool < warm**, neutral < warm**			1st > 3rd **	
DPG [°C]	2700 K	-1.3 $\pm$ 0.89	-2.4 $\pm$ 1.49	-3.3 $\pm$ 1.09	-2.4 $\pm$ 1.46	-1.5 $\pm$ 1.21	-1.8 $\pm$ 1.32	-3.0 $\pm$ 1.38
	6500 K	-1.6 $\pm$ 1.26	-2.4 $\pm$ 1.42					
		$p = 0.243$	$p = 0.952$	Cool > neutral**, cool > warm**, neutral > warm**			1st < 3rd **	
SBF hand	2700 K	1.0 $\pm$ 0.00	0.8 $\pm$ 0.74	0.40 $\pm$ 0.22	0.83 $\pm$ 0.58	1.29 $\pm$ 0.88	1.1 $\pm$ 0.58	0.6 $\pm$ 0.35
	6500 K	1.0 $\pm$ 0.00	0.9 $\pm$ 0.70					
		-	$p = 0.411$	Cool < neutral**, cool < warm**, neutral < warm*			1st $\approx$ 3rd ns	
SBF arm	2700 K	1.0 $\pm$ 0.00	0.9 $\pm$ 0.27	0.75 $\pm$ 0.28	0.83 $\pm$ 0.28	1.03 $\pm$ 0.32	0.9 $\pm$ 0.28	0.9 $\pm$ 0.39
	6500 K	1.0 $\pm$ 0.00	0.9 $\pm$ 0.36					
		-	$p = 0.750$	Cool $\approx$ neutral ns, cool < warm**, neutral < warm**			1st $\approx$ 3rd ns	

3.3. Effect of ambient temperature on alertness and thermophysiology

Participants reported to be less sleepy during the cool condition relative to the neutral or warm condition ($KSS_{neutral/warm} - KSS_{cool} = 2.4$ and $p < 0.01$). In line with this, the average PVT reaction time during the warm condition was longer compared to the neutral condition ($\beta = 0.025$ s, $p = 0.001$) and the cool condition ($\beta = 0.028$ s, $p < 0.001$) (Fig. 5A). The difference between the neutral and cool condition was not significant ($\beta = -0.0035$, $p = 0.624$).

$T_{mean skin}$, $T_{proximal}$ and T_{distal} were highest during the warm condition and lowest during the cool condition (all $p < 0.01$). The DPG was lowest during the cool condition and highest during the warm condition ($p < 0.01$). CBT was higher during the cool condition as

compared to neutral ($\beta = 0.09$ °C, $p = 0.001$) and warm ($\beta = 0.07$ °C, $p = 0.004$). CBT increased during the sessions, as shown by the difference between blocks 3 and 1 ($\beta = 0.04$ °C, $p = 0.034$) (Table 5). The cool condition resulted in a higher energy expenditure compared to the neutral and warm temperatures ($\beta = 0.25$, $p < 0.001$). Heart rate was lower during the cool versus the warm condition ($\beta = -6.0$ bpm, $p = 0.026$) and neutral versus warm ($\beta = -4.2$ bpm, $p = 0.045$) (Appendix A: Table A.1). As expected, thermal sensation was highest during the warm condition (1.25 ± 0.66) as compared to the neutral (0.05 ± 0.70) or to the cool condition (-1.39 ± 0.59) (both $p < 0.001$). Thermal comfort was highest during the thermoneutral condition ($p < 0.001$) (Appendix A: Table A.3).

In summary, the main findings concerning ambient temperature

Table 6R² of the Linear Mixed Model Equations for the subjective sleepiness.

Dependent variable: subjective sleepiness					
	Ambient temperature & CCT	Thermophysiological parameters (Eq. (2))	Thermophys. & CCT (Eq. (2) + CCT)	Perceived comfort parameters (Eq. (3))	Perceived comfort & CCT (Eq. (3) + CCT)
R ² _{Marginal}	0.26	0.36	0.36	0.54	0.54
R ² _{Conditional}	0.58	0.72	0.72	0.67	0.68

were a higher subjective sleepiness and longer PVT reaction time for the warm conditions (Fig. 1, arrow D). Skin temperatures increased with higher ambient temperatures along with a higher DPG (closer to 0). CBT and EE were higher during the cool condition as compared to the neutral and warm condition (Fig. 1, arrow E), while heart rate was lowest during the cool condition. Thermal sensation increased with an increasing ambient temperature, while thermal comfort was highest during the thermoneutral condition (Fig. 1, arrow F).

3.4. Mediator analyses for subjective sleepiness

The individual scores on the subjective sleepiness ranged from 2 ('very alert') till 9 ('extremely sleepy, fighting sleep'). The ambient temperature and the CCT exposure explained 26% of this variance (Table 6). Using the thermophysiological parameters, 36% of the variance in subjective sleepiness could be explained (marginal R² = 0.36, conditional R² = 0.72) (Table 6 and Appendix B: Tables B.4 and B.5). Backwards regression revealed the CBT, Tmeanskin and SBF_{hand} to be the independent variables that contributed significantly to the changes in subjective sleepiness (Eq. (2)) (Fig. 1, arrow G). Addition of the CCT as an independent variable did not significantly contribute to the estimated subjective sleepiness ($\beta_{\text{CCT}} = -0.28$, $p = 0.255$).

$$\text{Subjective Sleepiness} = 153.9 [-4.37 \cdot T_{\text{core}}] [+0.38 \cdot T_{\text{meanskin}}] [+1.03 \cdot \text{SBF}_{\text{hand}}] + G_{0i} + R_{ij} \quad (2)$$

Perceived comfort of the indoor environment was also associated with subjective sleepiness (Fig. 1, arrow H). Thermal sensation, valence and thermal comfort (TC) explained 54% of the variance in subjective sleepiness (Eq. (3)) (Table 6 and Appendix B: Table B.6). Again, addition of the CCT as an independent variable did not significantly improve the model ($\beta_{\text{CCT}} = -0.151$, $p = 0.533$) (Table 6).

$$\text{Subjective Sleepiness} = 11.05 [+0.78 \cdot \text{Sensation}] [-0.95 \cdot \text{Valence}] [+0.61 \cdot \text{TC}] + G_{0i} + R_{ij} \quad (3)$$

3.5. Mediator analyses for PVT reaction time

The individual average PVT reaction time ranged from 0.295 till 0.496 s. The explained variance using ambient temperature and CCT exposure was 11% (Table 7). The backwards regression revealed that the SBF_{underarm} and the DPG significant contributed to the prediction of the reaction time (Appendix B: Tables B.7 and B.8). However, the explained variance using these thermophysiological parameters was only 10% (marginal R²), while the conditional R² was 51% (Table 7) (Fig. 1: arrow G). On top of these physiological parameters, the CCT remained a

significant contributor to the predicted variance. CCT significantly ($p < 0.01$) affected reaction time when added to the model ($R^2_{\text{Marginal}} = 0.13$ and $R^2_{\text{Conditional}} = 0.56$) (Eq. (4)). Therefore, both influenced the reaction time (largely) independently.

$$\text{Reaction Time}_{\text{avg}} [\text{ms}] = 331.7 [+22.1 \cdot \text{SBF}_{\text{underarm}}] [+4.8 \cdot \text{DPG}] [+15.9 \cdot \text{CCT}_{6500\text{K}}] + G_{0i} + R_{ij} \quad (4)$$

For the perceived comfort parameters, thermal sensation and the perception of the light colour both correlated with PVT reaction time (Appendix B: Table B.9). A higher thermal sensation (warmer) led to slower responses, while a warmer perception of the colour of light was related to faster responses (Eq. (5)) (Fig. 1, arrow H). The marginal R² was 0.10 and the conditional R² was 0.55 (Table 7). Addition of CCT revealed that both independent variables "perception of light colour" and "CCT_{6500K}" became insignificant. This indicated that these variables were interdependent. Replacement of "perception of light colour" by "CCT_{6500K}" resulted in a significant contribution of "CCT_{6500K}" ($\beta_{\text{CCT}} = 14.3$, $p = 0.02$) (Table 6).

$$\text{Reaction Time}_{\text{avg}} [\text{ms}] = 361 [+8.4 \cdot \text{Sensation}] [-10.3 \cdot \text{Perception}_{\text{CCT}}] + G_{0i} + R_{ij} \quad (5)$$

The temperature effects might overrule the light induced alerting effects. Separate analyses on the differences between the two light sessions were performed to reveal whether a combination of several parameters might be associated with improved reaction times for the 2700 K sessions. Mixed model analyses revealed that $\Delta \text{SBF}_{\text{hand}}$ ($\Delta = 2700 \text{ K} - 6500 \text{ K}$) and ΔDPG were positively correlated with ΔRT ($R^2 = 0.24$). Surprisingly, the changes in visual comfort and perceived light colour were not significantly correlated with $\Delta \text{reaction time}$.

4. Discussion

The aim of this study was to explore the effect of CCT on alertness during morning hours and its interaction with ambient temperature. Surprisingly, participants had shorter reaction times on the PVT task during the 2700 K as compared to the 6500 K light exposures. The CCT did not affect subjective sleepiness. Conform our expectations, the 6500 K light exposures resulted in a higher CBT, however not significant after BH correction. The DPG and SBF were mediating factors for sleepiness and reaction times.

The tendency of a higher CBT during the light exposure of 6500 K could indicate that the 6500 K light enhanced the natural morning rise in CBT. Sato et al. also observed a higher CBT at high CCT (6500 K) during the first 2 h after waking up [20], combined with low melatonin levels. This could mean an increased CBT by acute melatonin

Table 7R² of the Linear Mixed Model Equations for the PVT reaction time.

Dependent variable: reaction time					
	Ambient temperature and CCT	Thermophysiological parameters	Thermophys. & CCT (Eq. (4))	Perceived comfort parameters (Eq. (5))	Perceived comfort & CCT (instead of "perception _{CCT} ")
R ² _{Marginal}	0.11	0.10	0.13	0.10	0.09
R ² _{Conditional}	0.57	0.51	0.56	0.55	0.54

suppression or (stronger) phase advance of the circadian rhythm. If the mechanism in our study was also based on melatonin suppression, then we would expect the CCT effects on CBT to be most pronounced during the first block when melatonin levels are expected to be higher as compared to the third block. However, the time of exposure had no effect on the light induced CBT increase. This makes it unlikely that melatonin dominated the light induced differences in CBT. In our previous study with the same exposure times in the morning, using bright (1200 lx) and dim light (5 lx), dim light resulted in a higher CBT and a smaller DPG [30]. This did not seem to be melatonin response either, since morning bright light is known for its (melatonin) phase advance ability [38] which should go along with a higher CBT. Maybe the effect of light is influenced by thermophysiology. Indeed, during the warm and cool conditions, but not during the neutral condition, 6500 K increased CBT compared to 2700 K. Heat loss mechanisms, like vasoconstriction and vasodilation, induced by temperature changes, might be influenced by CCT resulting in an altered CBT. However, DPG and skin blood flow were not significantly different between the CCT sessions. The combination of timing and the ambient temperature may be essential in obtaining CCT induced effects on CBT. A study including one temperature (for a longer duration) per morning session is required to confirm this hypothesis.

The study showed that thermophysiological parameters are correlated with subjective sleepiness and PVT reaction times. Subjective sleepiness was negatively correlated with CBT and positively correlated with mean skin temperature. Heat loss mechanisms (higher DPG and a higher SBF) were positively correlated to both a higher sleepiness and longer reaction times. These observations are in accordance with our hypotheses and with the literature on the association between thermoregulatory parameters and alertness: a higher skin temperature is associated with a higher subjective sleepiness [16]. Performance measures improve when CBT is higher [17] and the evening decline in CBT and increase in heat loss by vasodilation (higher DPG and SBF) are associated with increased sleepiness [18]. This study reveals that heat loss mechanisms are also involved in reduced alertness during the morning.

Perceived comfort ratings can be used as predictors for alertness as well. In accordance with the body temperature parameters, a warmer thermal sensation was associated with higher sleepiness and longer reaction times. This finding confirms those from other studies where higher thermal sensation reduced performance on office tasks [21]. In contrast, we observed that a warmer perception of the light colour was correlated with shorter reaction times. In the current study higher thermal comfort was associated with increased subjective sleepiness. However, office studies report improved productivity and alertness when participants felt thermally comfortable [22,39]. First, this discrepancy might be due to the temperature conditions used in those office studies, which were either around thermoneutrality or (slightly) warm. Warm conditions are associated with sleepiness and perceived as less comfortable compared to neutral. Secondly, this may be caused by the posture of the participants, who were lying in semi-supine position on a stretcher. Lying position reduces CBT and increases distal skin temperatures. This leads, under comfortable temperatures, to increased sleepiness [40].

In conclusion, PVT reaction times could not be very well explained (10%) using the thermophysiological parameters or the perceived comfort parameters. However, the perceived comfort parameters (Eq. (3)), can explain 54% of the variation in subjective sleepiness. Also, the thermophysiological parameters (Eq. (2)) improved the estimation of subjective sleepiness (36%) compared to the use of the environmental conditions (light and ambient temperature). So on top of environmental

conditions, data on the perceived comfort and body temperatures are required to effectively estimate subjective sleepiness.

The effect size of ambient temperature on the thermophysiological mediators for alertness was larger than the effects of CCT. Nevertheless, light induced changes in reaction time were positively correlated with the differences in skin blood flow and DPG between the light sessions ($R^2 = 0.24$; $p_{\text{SBF}} < 0.01$ and $p_{\text{DPG}} = 0.01$). This is remarkable because the shorter reaction times were observed in the 2700 K sessions where CBT was lower compared to the 6500 K sessions. Since it is expected that vasoconstriction would result in a higher CBT, this is not a consistent explanation of the reaction time improvement for the 2700 K exposures. The results are also not in line with studies performed in the evening/night and several studies performed during the day. For example a study of Chellappa et al. showed that light of 6500 K (rich in short wavelengths < 480 nm) in the evening leads to shorter reaction times of the PVT along with reduced melatonin levels compared to a low CCT [41]. Daytime studies do not always observe significant alertness improvements (or very limited) for higher CCT's [14,15]. The intensity of the light exposure could play a role in this respect. At an illuminance of 55 lx, the 2700 K exposures are perceived as more pleasing compared to 6500 K. However, at higher intensities (> 300 lx), a CCT of 6500 K is perceived as pleasing while a low CCT appears reddish [42]. Similarly, alerting effects of CCT may be dependent on its illuminance. Our hypothesis that (visual) comfort can influence reaction times on an auditory PVT was however not confirmed. This might be due to the two-sided effect of comfort: increasing sleepiness due to a higher comfort levels while improving reaction times by reducing cognitive load through minimizing discomfort.

5. Conclusion

Taken together, higher subjective sleepiness and longer PVT reaction times are associated with lower body temperature and higher perceived comfort. Ambient temperature plays a major role in this correlation. Skin temperatures (distal and proximal) are easy to measure and therefore are practical predictors for alertness. Implementation of these parameters in climate systems may contribute to productivity improvements. The low CCT exposure resulted in shorter reaction times and lower CBT. There was no clear relationship between alerting effect of light and thermophysiological parameters or perceived comfort. Both alertness outcomes, subjective sleepiness and reaction times, were for a large part dependent on the participants; meaning some participants were generally more sleepy/had a longer reaction times. Since the prediction of alertness was highly improved when taking into account the individual intercept, individually tuned climate systems are recommended. It remains to be tested if light CCT (and intensity) plays a role in this correlation or if it can be used as an “add-on” effect.

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Conflict of interest

Luc Schlangen and Jan Souman are employees of Philips Lighting, the Netherlands.

Appendix A: Effects of CCT, ambient temperature and time of block.

Table A.1

Mean $\pm$ sd of the physiological parameters per CCT, temperature condition and block number (The thermoneutral condition is during the 2nd block). In case the interaction between CCT and temperature/block was not significant, the mean of both CCT exposures was reported per temperature/block. Dependent parameters are: Energy expenditure (EE), Energy expenditure relative to baseline (EE_{rel}), Heart rate (HR), Blood pressure systolic (BPS), Blood pressure diastolic (BPD) and Mean arterial pressure (MAP). #p < 0.10, *p < 0.05 and **p < 0.01.

Parameter	Session	Baseline	CCT exposure	Temperature			Time	
				Cool	Thermoneutral/2nd block	Warm	1st block	3rd block
EE [kJ/min]	2700 K	4.4 $\pm$ 0.33	4.5 $\pm$ 0.35	4.7 $\pm$ 0.37	4.5 $\pm$ 0.32	4.4 $\pm$ 0.29	4.5 $\pm$ 0.32	4.6 $\pm$ 0.42
	6500 K	4.3 $\pm$ 0.30	4.5 $\pm$ 0.33					
		p = 0.114	p = 0.302	Cool > neutral**, cool > warm**, neutral $\neq$ warm ns			1st $\neq$ 3rd ns	
EE _{rel}	2700 K	1.0 $\pm$ 0.00	1.0 $\pm$ 0.05	1.1 $\pm$ 0.06	1.0 $\pm$ 0.04	1.0 $\pm$ 0.04	1.0 $\pm$ 0.04	1.1 $\pm$ 0.06
	6500 K	1.0 $\pm$ 0.00	1.1 $\pm$ 0.05					
		–	p = 0.095	Cool > neutral**, cool > warm**, neutral $\neq$ warm ns			1st $\neq$ 3rd ns	
HR [bpm]	2700 K	67 $\pm$ 8.9	67 $\pm$ 8.0	66 $\pm$ 7.5	66 $\pm$ 9.4	69 $\pm$ 8.6	67 $\pm$ 9.4	68 $\pm$ 8.3
	6500 K	67 $\pm$ 7.9	67 $\pm$ 9.2					
		p = 0.685	p = 0.597	Cool $\neq$ neutral ns, cool < warm**, neutral < warm*			1st $\neq$ 3rd ns	
BP systolic [mmHg]	2700 K	111 $\pm$ 8.7	110 $\pm$ 8.0	113 $\pm$ 7.1	111 $\pm$ 7.7	108 $\pm$ 7.3	109 $\pm$ 6.1	112 $\pm$ 8.6
	6500 K	110 $\pm$ 8.6	111 $\pm$ 7.2					
		p = 0.623	p = 0.330	Cool > neutral**, cool > warm**, neutral $\neq$ warm ns			1st < 3rd *	
BP diastolic [mmHg]	2700 K	66 $\pm$ 5.4	66 $\pm$ 4.6	67 $\pm$ 4.8	66 $\pm$ 3.6	64 $\pm$ 4.6	65 $\pm$ 3.8	66 $\pm$ 5.8
	6500 K	65 $\pm$ 3.4	66 $\pm$ 4.4					
		p = 0.311	p = 0.630	Cool > neutral**, cool > warm**, neutral > warm*			1st < 3rd *	
MAP [mmHg]	2700 K	81 $\pm$ 6.2	81 $\pm$ 5.1	82 $\pm$ 4.8	81 $\pm$ 4.8	79 $\pm$ 4.8	80 $\pm$ 3.8	81 $\pm$ 6.0
	6500 K	80 $\pm$ 5.0	81 $\pm$ 4.8					
		p = 0.479	p = 0.330	Cool > neutral**, cool > warm**, neutral > warm*			1st < 3rd *	

Table A.2

Plasma melatonin levels at baseline for each session (Mean $\pm$ SEM) and plasma cortisol level mean values per light session, temperature condition and block number (Mean $\pm$ stdev). Since the interaction between CCT and temperature/block was not significant, the mean of both CCT exposures was reported per temperature/block. #p < 0.10, *p < 0.05 and **p < 0.01.

Parameter	Session	Baseline	CCT exposure	Temperature			Time	
				Cool	Thermoneutral/ 2nd block	Warm	1st block	3rd block
Plasma Melatonin [pg/ml]	2700 K	40.8 $\pm$ 6.16	N/A	N/A	N/A	N/A	N/A	N/A
	6500 K	39.6 $\pm$ 5.94	N/A					
		p = 0.581		–			–	
Cortisol [μ mol/ l]	2700 K	0.75 $\pm$ 0.04	0.54 $\pm$ 0.03	0.55 $\pm$ 0.04	0.50 $\pm$ 0.03	0.53 $\pm$ 0.04	0.64 $\pm$ 0.04	0.43 $\pm$ 0.03
	6500 K	0.71 $\pm$ 0.04	0.51 $\pm$ 0.03					
		p = 0.053	p = 0.046	Cool > neutral**, cool $\neq$ warm ns, neutral $\neq$ warm ns			1st > 3rd **	
Cortisol change from baseline [μ mol/l]	2700 K	0.0 $\pm$ 0.0	–0.21 $\pm$ 0.02	–0.18 $\pm$ 0.03	–0.22 $\pm$ 0.02	–0.20 $\pm$ 0.03	–0.08 $\pm$ 0.02	–0.29 $\pm$ 0.02
	6500 K	0.0 $\pm$ 0.0	–0.19 $\pm$ 0.02					
		–	p = 0.520	Cool $\neq$ neutral ns, cool $\neq$ warm ns, neutral $\neq$ warm ns			1st < 3rd **	

Table A.3

Perceived comfort during the different light sessions, temperature conditions and block numbers (Mean $\pm$ stdev). In case the interaction between CCT and temperature/block was not significant, the mean of both CCT exposures was reported per temperature/block.). #p < 0.10, *p < 0.05 and **p < 0.01.

Parameter	Session	Baseline	CCT exposure	Temperature			Time	
				Cool	Thermoneutral/ 2nd block	Warm	1st block	3rd block
Thermal sensation	2700 K	0.0 $\pm$ 0.75	0.0 $\pm$ 1.17	−1.4 $\pm$ 0.59	0.1 $\pm$ 0.7	1.3 $\pm$ 0.66	0.1 $\pm$ 1.46	−0.2 $\pm$ 1.48
	6500 K	0.2 $\pm$ 0.96	0.0 $\pm$ 1.36					
		p = 0.387	p = 0.980	Cool < neutral**, cool < warm**, neutral < warm**			1st > 3rd *	
Thermal Comfort	2700 K	0.7 $\pm$ 0.55	0.4 $\pm$ 0.79	−0.2 $\pm$ 0.5	0.9 $\pm$ 0.6	0.4 $\pm$ 0.81	0.1 $\pm$ 0.76	0.1 $\pm$ 0.73
	6500 K	0.6 $\pm$ 0.49	0.3 $\pm$ 0.77					
		p = 0.356	p = 0.542	Cool < neutral**, cool < warm**, neutral > warm**			1st $\neq$ 3rd ns	
Perceived light intensity	2700 K	−0.9 $\pm$ 0.80	0.2 $\pm$ 0.66	0.6 $\pm$ 0.78	0.1 $\pm$ 0.52	0.4 $\pm$ 0.72	0.8 $\pm$ 0.77	0.2 $\pm$ 0.6
	6500 K	−0.7 $\pm$ 0.88	0.5 $\pm$ 0.70					
		p = 0.355	p = 0.001	Cool $\neq$ neutral ns, cool $\neq$ warm ns, neutral $\neq$ warm ns			1st > 3rd **	
Visual comfort intensity	2700 K	0.6 $\pm$ 0.61	0.7 $\pm$ 0.54	0.6 $\pm$ 0.73	0.7 $\pm$ 0.55	0.6 $\pm$ 0.54	0.5 $\pm$ 0.73	0.7 $\pm$ 0.52
	6500 K	0.4 $\pm$ 0.65	0.6 $\pm$ 0.67					
		p = 0.310	p = 0.395	Cool $\neq$ neutral ns, cool $\neq$ warm ns, neutral $\neq$ warm ns			1st > 3rd **	
Perceived light colour	2700 K	0.3 $\pm$ 0.83	0.1 $\pm$ 0.56	−0.5 $\pm$ 0.79	−0.3 $\pm$ 0.71	−0.2 $\pm$ 0.8	−0.4 $\pm$ 0.85	−0.3 $\pm$ 0.76
	6500 K	0.3 $\pm$ 0.69	−0.8 $\pm$ 0.65					
		p = 0.980	p < 0.001	Cool $\neq$ neutral ns, cool < warm*, neutral $\neq$ warm ns			1st $\neq$ 3rd ns	
Visual comfort colour	2700 K	0.7 $\pm$ 0.55	0.7 $\pm$ 0.48	0.5 $\pm$ 0.64	0.6 $\pm$ 0.52	0.6 $\pm$ 0.53	0.4 $\pm$ 0.59	0.7 $\pm$ 0.56
	6500 K	0.7 $\pm$ 0.65	0.4 $\pm$ 0.60					
		p = 0.938	p < 0.001	Cool $\neq$ neutral ns, cool $\neq$ warm ns, neutral $\neq$ warm ns			1st > 3rd **	
Valence	2700 K	6.5 $\pm$ 1.1	6.4 $\pm$ 1.2	6.3 $\pm$ 1.2	6.7 $\pm$ 1.2	6.4 $\pm$ 1.1	6.2 $\pm$ 1.2	6.5 $\pm$ 1
	6500 K	6.4 $\pm$ 1.2	6.4 $\pm$ 1.1					
		p = 0.594	p = 0.820	Cool $\neq$ neutral ns, cool $\neq$ warm ns, neutral $\neq$ warm ns			1st $\neq$ 3rd ns	
Arousal	2700 K	2.3 $\pm$ 1.1	2.4 $\pm$ 1.2	2.8 $\pm$ 1.4	2.2 $\pm$ 1.2	2.0 $\pm$ 1	2.2 $\pm$ 1	2.6 $\pm$ 1.5
	6500 K	2.3 $\pm$ 1.3	2.3 $\pm$ 1.3					
		p = 0.849	p = 0.596	Cool $\neq$ neutral ns, cool $\neq$ warm ns, neutral $\neq$ warm ns			1st < 3rd *	

Appendix B: Mediating factors analyses

Mediating factors of subjective sleepiness

Table B.4

Skin temperature parameter selection for the prediction of subjective sleepiness. The mixed model including mean skin temperature resulted in the highest explained variance of the dependent variable.

	Full model Mean SKT		Full model Tprox		Full model Tdistal		Full model DPG	
	β	p-Value	β	p-Value	β	p-Value	β	p-Value
Intercept	150.7	0.001	159.47	0.000	146.7	0.000	161.2	0.000
Tcore	−4.23	0.000	−4.51	0.000	−3.94	0.000	−4.09	0.001
HR	−0.066	0.008	−0.077	0.007	−0.077	0.007	−0.063	0.027
SBF _{hand}	1.02	0.000	1.04	0.000	1.07	0.000	1.33	0.000
SBF _{underarm}	0.113	0.781	0.206	0.608	0.144	0.721	0.274	0.509
TmeanSKT	0.470	0.000	–	–	–	–	–	–
Prox SKT	–	–	0.517	0.002	–	–	–	–

Distal SKT	–	–	–	–	0.284	0.000	–	–
DPG	–	–	–	–	–	–	0.295	0.027
$R^2_{\text{GLMM}(m)}$	0.393		0.392		0.389		0.381	
$R^2_{\text{GLMM}(c)}$	0.785		0.788		0.797		0.775	

Table B.5

Backwards elimination of the mixed model including physiological parameters to estimate subjective sleepiness (Model 3).

	Full model		Model 2		Model 3		Model 4	
	β	p-Value	β	p-Value	β	p-Value	β	p-Value
Intercept	150.7	0.001	150.4	0.001	153.87	0.001	182.40	0.000
Tcore	– 4.23	0.000	– 4.23	0.000	– 4.37	0.000	– 4.79	0.000
SBF _{hand}	1.02	0.000	1.03	0.000	1.03	0.000	1.51	0.000
TmeanSKT	0.47	0.000	0.48	0.001	0.38	0.008	–	–
HR	– 0.066	0.008	– 0.07	0.010	–	–	–	–
SBF _{underarm}	0.113	0.781	–	–	–	–	–	–
$R^2_{\text{GLMM}(m)}$	0.393		0.393		0.361		0.355	
$R^2_{\text{GLMM}(c)}$	0.784		0.783		0.717		0.689	
AIC	335.2		337.1		339.5		350.2	

Table B.6

Backwards elimination of the mixed model including perceived comfort parameters to estimate subjective sleepiness (Model 5).

	Full model		Model 2		Model 3		Model 4		Model 5		Model 6	
	β	p-Value	β	p-Value	β	p-Value	β	p-Value	β	p-Value	β	p-Value
Intercept	11.41	0.000	11.41	0.000	11.44	0.000	10.53	0.000	11.05	0.000	9.45	0.000
Thermal sensation	0.724	0.000	0.725	0.000	0.720	0.000	0.784	0.000	0.777	0.000	0.899	0.000
Valence	– 0.949	0.000	– 0.952	0.000	– 0.943	0.000	– 0.890	0.000	– 0.948	0.000	– 0.674	0.000
Thermal Comfort	0.610	0.002	0.611	0.002	0.637	0.001	0.629	0.001	0.607	0.001	–	–
Perception Intensity	0.400	0.051	0.388	0.051	0.369	0.057	0.366	0.063	–	–	–	–
Arousal	– 0.231	0.095	– 0.232	0.093	– 0.237	0.087	–	–	–	–	–	–
Comfort light	0.095	0.764	0.123	0.680	–	–	–	–	–	–	–	–
Perception colour	0.045	0.807	–	–	–	–	–	–	–	–	–	–
$R^2_{\text{GLMM}(m)}$	0.558		0.557		0.556		0.556		0.543		0.452	
$R^2_{\text{GLMM}(c)}$	0.696		0.696		0.696		0.678		0.673		0.660	
AIC	331.9		332		332.1		332.9		334.3		341.6	

Model environmental conditions:

Subjective sleepiness = $5.56 - 1.31 * \text{Temp}_{\text{Cool}} + 1.25 * \text{Temp}_{\text{warm}} - 0.29 * \text{Light}_{6500\text{K}}$ R^2_{marginal} : 0.259, $R^2_{\text{conditional}}$: 0.581.*Mediating factors of reaction time*

Table B.7

Skin temperature parameter selection for the prediction of reaction time. The mixed model including the DPG resulted in the highest explained variance of the dependent variable.

	Full model Mean SKT		Full model Prox		Full model Distal		Full model DPG	
	$\beta * 10^3$	p-Value	$\beta * 10^3$	p-Value	$\beta * 10^3$	p-Value	$\beta * 10^3$	p-Value
Intercept	222.0	0.844	285.8	0.797	62.47	0.956	99.61	0.929
Tcore	– 0.163	0.996	– 1.92	0.947	4.510	0.880	5.597	0.853
TmeanSKT	2.457	0.526	–	–	–	–	–	–
HR	0.653	0.333	0.665	0.3241	0.603	0.368	0.656	0.321
SBF _{hand}	4.634	0.496	5.028	0.459	3.742	0.566	5.111	0.385
SBF _{underarm}	18.01	0.096	18.63	0.080	16.84	0.118	17.14	0.109
Prox SKT	–	–	2.409	0.577	–	–	–	–

Distal SKT	–	–	–	–	2.299	0.315	–	–
DPG	–	–	–	–	–	–	3.486	0.300
R ² _{GLMM(m)}	0.097		0.096		0.103		0.111	
R ² _{GLMM(c)}	0.494		0.493		0.501		0.503	
AIC	941.4		941.5		940.8		940.8	

Table B.8

Backwards elimination of the mixed model including physiological parameters to estimate reaction time (Model 4).

	Full model		Model 2		Model 3		Model 4		Model 5	
	$\beta \times 10^3$	p-Value	$\beta \times 10^3$	p-Value	$\beta \times 10^3$	p-Value	β	p-Value	β	p-Value
Intercept	99.61	0.929	306.7	0.000	307.5	0.000	356.5	0.000	338.0	0.000
SBF _{underarm}	17.14	0.109	17.21	0.107	19.49	0.060	21.06	0.041	28.28	0.003
DPG	3.486	0.300	3.289	0.303	4.349	0.145	4.894	0.099	–	–
HR	0.656	0.321	0.669	0.309	0.730	0.264	–	–	–	–
SBF _{hand}	5.111	0.385	5.116	0.385	–	–	–	–	–	–
Tcore	5.597	0.853	–	–	–	–	–	–	–	–
R ² _{GLMM(m)}	0.11		0.11		0.11		0.10		0.07	
R ² _{GLMM(c)}	0.50		0.50		0.50		0.51		0.49	
AIC	940.8		941.2		945.8		946.6		965.1	

Table B.9

Backwards elimination of the mixed model including perceived comfort parameters to estimate reaction time (Model 4).

	Full model		Model 2		Model 3		Model 4		Model 5	
	β	p-Value	β	p-Value	β	p-Value	β	p-Value	β	p-Value
Intercept	329	0.000	328	0.000	362	0.000	361	0.000	364	0.000
Thermal sensation	11.1	0.000	11.0	0.000	9.5	0.000	8.4	0.000	7.8	0.0012
Perception colour	– 10.1	0.037	– 9.3	0.029	– 9.4	0.028	– 10.3	0.016	–	–
Thermal Comfort	– 7.3	0.158	– 6.9	0.160	– 4.8	0.252	–	–	–	–
Valence	3.4	0.477	3.7	0.432	–	–	–	–	–	–
Arousal	4.5	0.235	4.4	0.245	–	–	–	–	–	–
Perception Intensity	– 1.1	0.834	–	–	–	–	–	–	–	–
Comfort light	2.2	0.795	–	–	–	–	–	–	–	–
R ² _{GLMM(m)}	0.139		0.136		0.115		0.104		0.064	
R ² _{GLMM(c)}	0.579		0.579		0.569		0.551		0.502	
AIC	359.9		363.8		366.1		366.8		373.0	

Model environmental conditions:

Reaction time = $335 - 4 * \text{Temp}_{\text{Cool}} + 0.025 * \text{Temp}_{\text{warm}} + 0.014 * \text{Light}_{6500\text{K}}$.R²_{marginal}: 0.112, R²_{conditional}: 0.565.

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