Personal control of correlated color temperature of light

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Personal control of correlated color temperature of light: Effects on thermal comfort, visual comfort, and cognitive performance

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ABSTRACT

Recent studies have suggested that thermal and visual comfort are correlated, although the causality underlying this correlation is unclear. Personal control of correlated color temperature (CCT) provides individual visual comfort, but its effects on other parameters such as thermal comfort and cognitive performance remain underexamined. Therefore, we investigated if personal control of CCT can, on top of visual comfort, enhance thermal comfort and cognitive performance in office scenarios while exposed to mild cold (17 °C) using a 2x2 within-subject design. Sixteen participants were initially exposed to CCT of either 2700 K or 5700 K for 70 min. In the subsequent 70 min, participants either had free control of CCT or no control. As expected, personal control of CCT improved visual comfort and mitigated perceived eye-related symptoms. However, it did not significantly affect thermal comfort for either antecedent CCT. When the antecedent CCT was 5700 K, personal control of CCT increased alertness and physiological arousal, improved the planning and verbal cognitive performance, but, unexpectedly, decreased performance on mental spatial manipulation tasks. Additional analyses then explored the role of the psychological and personalization effects of personal control by controlling for the actual CCT. These suggest that control benefited visual comfort, eye-related symptoms, perceived task performance, pleasure, alertness and physiological arousal. This study is one of the first studies to demonstrate that visual comfort does not causally affect thermal comfort. Personal control of CCT benefits visual appraisals and eye-related symptoms, sometimes improves alertness, but differentially influences cognitive performance depending on the task type.

1. Introduction

Indoor environments are paramount to occupants' comfort, health and productivity since people spend most of their time indoors [1,2]. Indoor environmental conditioning also accounts for a large portion of buildings' energy consumption. For example, indoor temperature control accounts for ~50% of this [3,4]. Meanwhile, occupants are continuously exposed to multiple indoor environmental stimuli, including temperature, light, sound, and other factors. Understanding how these stimuli interact helps to design indoor environments that are beneficial for occupants at a minimal energy use. As one of many interactions, the light-temperature interaction has received increasing attention [5–9]. Relaxing indoor temperature ranges and allowing seasonal variations, like accepting lower temperatures in winter, can save building energy consumption for indoor temperature control, and may even benefit human (metabolic) health [10–12]. For example, allowing the temperature setpoint to fluctuate daily and seasonally can even save up to 50–70% energy in some case studies [11,13]. However, such variations in indoor temperature may challenge occupants' needs for thermal comfort and performance. Light has shown the potential to address these challenges [7,14] as both correlated color temperature (CCT) and illuminance have been suggested to affect thermal perceptions [15]. For example, several studies found that a low CCT is associated with a warmer thermal sensation [14,16–19] and, therefore, a low CCT may improve thermal comfort in cold conditions. On the other hand, literature also reported null effects [7,14,17,18] and a significant effect showing high CCT improves thermal comfort in cold conditions [20]. These inconsistent findings can be attributed to methodological differences, such as exposure durations, time of the day, thermal conditions, and light characteristics, as well as participants' characteristics

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[15,16,18,20].

More recently, studies on the light-temperature interaction revealed that thermal comfort is positively correlated with visual comfort. One of the first suggestions for this mechanism was presented in te Kulve et al. [7]. They tested the effects of CCT (2700 K vs. 5700 K) and illuminance (5 lux vs. 1200 lux) on thermal comfort. Their results showed that a change in thermal comfort was positively associated with a change in visual comfort under a cool (26 °C with 0.04 clo) and a warm environment (32 °C with 0.04 clo), and this association was insignificant in a neutral thermal condition (29 °C with 0.04 clo). These findings suggest that thermal discomfort is required for the interactions between visual comfort and thermal comfort [7]. This visual-thermal comfort association was further confirmed by Kompier et al. [6], Lechner et al. [21], Luo et al. [20], and Yan et al. [22] under different light conditions and temperatures in both laboratory and field studies. For example, Luo et al. [20] measured thermal perceptions under two CCT scenarios (2700 K vs. 5700 K) in a cool condition (17 °C with 0.8 clo), and a positive association was found between thermal comfort and visual comfort. These repeated findings in various contexts suggest that the visual-thermal comfort association is neither a serendipitous discovery nor a special case only relevant under very specific conditions. However, the above-mentioned associations were correlational in nature: no causal relations have been tested so far. Therefore, whether light may be used to improve thermal comfort via increasing visual comfort remains an open question to date.

Using a light setting to improve visual comfort and thereby thermal comfort is complicated because of substantial inter-individual and intra-individual differences in which lighting conditions are experienced as visually comfortable [23–26]. The inter-individual variability may partially depend on personal characteristics, such as age, gender or general preferences. The intra-individual variability may rest on, for example, a person's mental state (e.g., level of alertness [27]) or the task at hand [26]. One way to address this variability is to give people personal control over the light settings. Personal control allows adjustments of objective lighting conditions to personal preferences. Moreover, it also provides a sense of having control, which has been implied to reduce stress reactions [28,29]. Furthermore, having control over one aversive stimulus may ameliorate the negative effects of another aversive stimulus [30–32], which suggests that thermal discomfort may be further mitigated by having control over lighting.

Besides the potential to improve thermal comfort, personal control of light may have additional benefits in an office environment. Literature on personal control of light mainly focused on the personal control over illuminance. It has been suggested that obtaining individually preferred illuminances by personal control improves satisfaction with the lighting [33–35], affect [33,34], well-being [36], work engagement [37,38] and performance [39,40], although some null effects were also reported [26, 41]. In contrast to the interest in personal control of illuminance, personal control of CCT has received far less attention. Most research regarding personal control of CCT has centered on CCT preference [42, 43], whereas the effects of personal control on the occupants, such as on well-being and performance, remain largely unexamined. On the other hand, most color-tunable lighting systems have become energy efficient and tuning the lighting's CCT requires limited additional energy consumption [17,44]. These advancements in color-tunable systems facilitate the opportunity to provide personal control of CCT.

As causality behind the visual-thermal comfort association is unclear and very little is currently known about how personal control of CCT affects well-being and cognition, the current study tested the impact of personal control of CCT in an office-like scenario. We aimed to answer two questions: 1) Does personal control of CCT improve thermal comfort by enhancing visual comfort in mild cold? 2) Does personal control of CCT benefit cognitive performance, eye-related symptoms, alertness, pleasure and arousal? The results were also used to further explore the psychological ("perceived control") and personalization ("having exercised control") effects of personal control vis-à-vis the effects of the objective light condition.

2. Method

2.1. Participants and ethical considerations

In total, sixteen participants (eight females taking hormonal contraception and eight males) gave informed consent and completed the study during summer and fall in the Netherlands. All participants were healthy, normal chronotype, 18–40 years old with a BMI of 18.0–27.5 kg/m^2, and living in or near the Netherlands for more than two months.

The medical-ethical committee of Maastricht University approved this study, which was carried out in accordance with the Declaration of Helsinki. Parts of this study have been previously reported in an article focusing on *the effects of CCT* itself [20]. The current article focuses on the effects of *personal control of CCT*.

2.2. Experiment protocol

2.2.1. Study design

Considering that the effects of personal control may depend on the antecedent conditions, this study tested personal control vs. no control scenarios in combination with two antecedent CCTs (2700 K and 5700 K) in a fully within-subject design, see Fig. 1. The participants attended the four scenarios on four different days. A 4 × 4 Latin square design was used to balance the order of the scenarios. The four scenarios for a participant were scheduled within a month to avoid seasonal effects. Moreover, the interval between any two scenarios was more than one day to reduce any short-term acclimation induced by the study intervention. In addition, all four scenarios for a participant started at the same time of day, either 9:00–12:00 h or 13:00–16:00 h. Between participants, the sessions were evenly distributed over the day.

The study was conducted in a windowless climate chamber at Maastricht University [45]. Each scenario included three periods (Fig. 1):

- Period 0 – Stabilization (30 min): Participants reside in a thermo-neutral and visual neutral condition to stabilize the state of their body (3700 K, 23 °C, predicted mean votes (PMV) = ~0).
- Period 1 - Creating discomfort (70 min): Previous literature suggests that the thermal-visual association only appears in uncomfortable conditions [7]. Therefore, participants stayed in a thermally uncomfortable condition, with an air temperature generally perceived as uncomfortably cold (17 °C, PMV = ~-1.65). The CCT started with either low or high CCT (2700 K or 5700 K), which are commonly found in office settings.
- Period 2 – Testing (70 min): This period was intended to test the effects of personal control vs. no control. In the personal control scenarios, the participants were offered the opportunity to change the CCT in the first 10 min. In the no control scenarios, the CCT remained the same as in Period 1. The thermal conditions were kept the same as in Period 1.

Across the four scenarios, illuminance was fixed at 498.9 ± 5.2 lux at the eye, air temperature at 17.2 °C±0.3 °C, the mean radiant temperature at 17.2 °C±0.2 °C, the relative humidity at 40–48%, and the air speed at 0.15–0.26 m/s. In addition, participants performed office tasks (~1.2 met), and clothing insulation value was standardized at 0.8 clo (underwear, long-sleeve shirt, sweatpants, socks, shoes and office chair insulation).

2.2.2. Personal lighting system

The personal lighting system consisted of two Hue Aurelle Rectangular Lights (Signify) that measure 120 by 30 cm, of which one was mounted on the ceiling, and another was placed on the desk (see

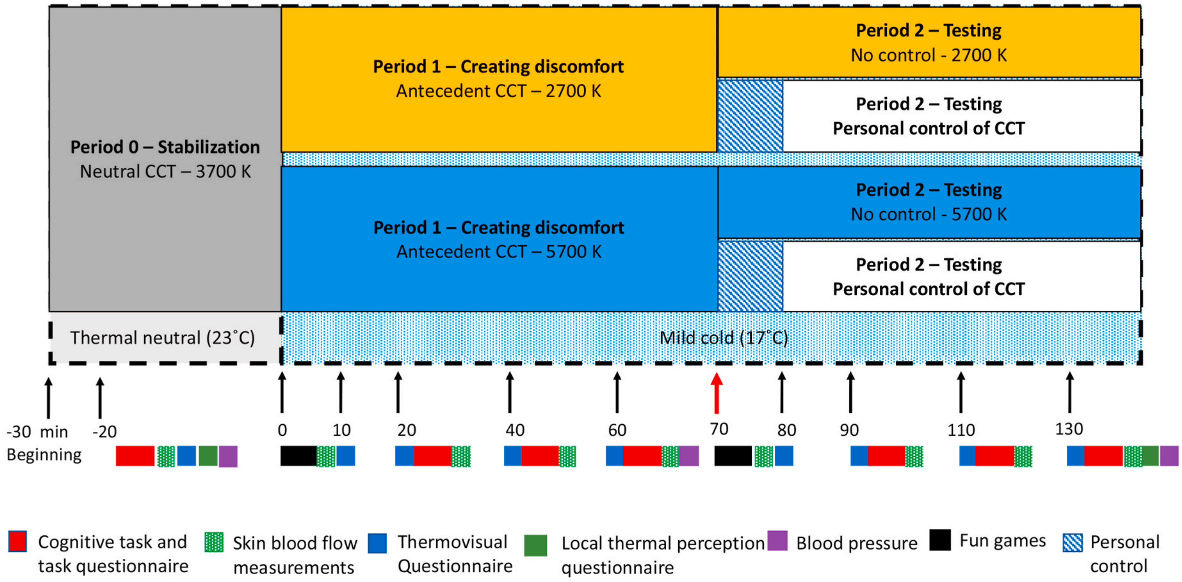

Fig. 1. Experimental design. Personal control of light (personal control: Yes/No) was combined with two antecedent CCTs (2700 K/5700 K), resulting in four scenarios. Illuminance was kept constant at ~500 lux at the eye. The red arrow indicates the beginning of the 10-min personal control phase. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. S1). The participants faced the desk light and used a laptop screen to mimic office activities. The illuminance of the laptop screen was fixed at a low level to reduce the light variation when different screen activities were performed. When participants had personal control over CCT, they controlled the ceiling and the desk light simultaneously. As the recommended minimum melanopic EDI (equivalent daylight illuminance) to promote healthy lighting is 250 lux at the eye [46], a photopic illuminance of 500 lux at eye level is chosen, which led to melanopic EDIs in this study varying between 209 lux and 409 lux (Table S1). As the directionality between the light and the eye may influence the effects of light [47], the illuminance came from the desk light and the laptop screen was kept constant at ~420 lux, and the ceiling light contributed the remaining ~80 lux. Overall, the participants could control the light using two buttons (UP and DOWN) that allowed them to navigate between 2700 K and 5700 K in 20 perceptually equal steps in the personal control scenarios. The designed CCT range matches that found in most office settings, with 3500–4000K as the most common and preferred value [48,49], as well as in numerous earlier studies [7,14,16–18,25,50]. The detailed light characteristics for each step are shown in Table S1.

2.2.3. Experimental procedure

Participants firstly completed a screening visit to determine their eligibility for this study. Eligible participants attended a pre-experimentation visit to acquaint themselves with the test setup and process, where they practiced the cognitive tasks for 1.5 h to reduce the impact of learning effects in the actual tests. They were asked to try their best to score higher in the tasks, but no performance-dependent monetary incentive was given.

The participants were instructed to have a similar 24 h lifestyle (food, drinks, sleep and physical activity) before each scenario to reduce variations in participants' states on the testing days. On the test day, participants arrived at either 9:00 h without breakfast or 13:00 h without lunch. Upon arrival, they stayed in a respiration chamber with a thermally and visually neutral environment, and the researchers provided a standardized meal. Next, self-reports of last night's bedtimes and sleep duration were collected. The participants wore standardized clothing and some sensors, including wireless skin temperature sensors, a heart rate belt, a skin blood flow sensor, a physical activity monitor and a blood pressure monitor cuff. Skin temperature, heart rate measures and physical activity were monitored continuously.

After these preparations, Period 0 started (Fig. 1). Participants sat on an office chair and performed office tasks for 30 min. At timestamp t = −20 min, the cognitive tasks, blood pressure measurements, and skin blood flow measurements were performed. In addition, they filled in the task questionnaire probing subjective perceptions towards the tasks, and the experience questionnaire regarding subjective perceptions of the environment.

Upon completion of Period 0, the participants were transferred to another chamber and were exposed to the prescribed thermally uncomfortable conditions for 70 min (Period 1, 2700 K or 5700 K, 17 °C, Fig. 1). The participants were given some video games, like Candy Crush, for the first 10 min. The experience questionnaire and skin blood flow measurements were completed at t = 10, 20, 40, and 60 min. Cognitive tasks and the task questionnaire were scheduled at t = 20, 40 and 60 min. In addition, blood pressure was gauged at the end of Period 1 (t = 60min).

Period 2 lasted for 70 min and was identical to Period 1 except that personal control of CCT was available in the first 10 min of Period 2. At the beginning of Period 2, the participants were again given some video games for the first 10 min to relax. In the personal control scenarios, the participants had the opportunity to control the light settings at their desire within the first 10 min, after which it stayed constant in that setting. On the other hand, the lighting setting in the no control scenarios remained the same as in Period 1. The experience questionnaire was provided at timestamps t = 80, 90, 110, and 130 min. Cognitive tasks and the task questionnaire were scheduled at t = 90, 110, and 130 min. Furthermore, the local thermal perceptions questionnaire and blood pressure measurement were scheduled at the end of Period 2 (t = 130min).

2.3. Measurements

Detailed information on the measurements can be found in our previous article [20].

2.3.1. Environmental measurements

To measure the light, a spectrometer (MK350D, UPRtek) was placed in the vertical plane at eye level facing the desk light and laptop. The air temperature near the participants was measured by iButtons at 0.1 m, 0.6 m, and 1.1 m from the ground (DS1922L, Maxim Integrated, accuracy: ±0.5 °C, range: −40 to 85 °C). A climate measurement station (Almemo 2890–9, Ahlborn) was used to measure the mean radiant temperature (accuracy: ±0.3 °C, range: −50 to 200 °C), air speed (accuracy: 3% of the measured value, range: 0.05–1 m/s), and relative air humidity (accuracy: ±1.3%, range: 0–98%) at 0.6 m from the ground.

2.3.2. *Participants' characteristics*

Body composition was measured using an air displacement plethysmograph (Bodpod, Cosmed). The body surface area was calculated based on the Du Bois formula [51]. Additionally, the Munich Chronotype Questionnaire was used to assess participants' chronotypes [52].

2.3.3. *Experience questionnaire*

The experience questionnaire comprised the following four parts.

Thermal appraisal questions included whole-body thermal sensation, preference, acceptance, comfort and pleasantness and perceived shivering, constructed based on the ISO standard 1055 [53]. The visual analogue scale was used to measure thermal appraisals (Fig. S2), except for thermal acceptance, for which a binary scale ('acceptable' or 'unacceptable') was employed. Local thermal sensations and comfort of nine body parts were also assessed using the visual analogue scale, including head, neck, torso, upper arm, lower arm, hand, thigh, calf and feet (Figs. S2a and b). The thermal comfort rate was calculated as the percentage of the votes equal or higher than 'just comfortable'.

Visual appraisal questions contained questions on sensation and preference of color and illuminance of the lighting, visual acceptance, visual comfort and visual pleasantness. Similar to thermal appraisals, the visual acceptance was measured by a binary scale and other visual appraisal outcomes were assessed using visual analogue scales adopted from previous literature [7,25] (Fig. S3).

Eye-related symptoms covered eye strain, eye discomfort and eye fatigue, which were probed by scales from Viola et al. [54] (Fig. S4a).

Alertness was measured by the Karolinska sleepiness scale [55] (Fig. S4b). In addition, two components of affect (*pleasure* and *arousal*) were assessed using self-assessment manikin scales [56] (Figs. S4c and d).

2.3.4. *Physiological parameters*

Mean skin temperature was measured by iButtons (DS1922L, Maxim Integrated, accuracy: ±0.5 °C, range: −40 to 85 °C) placed at 14 sites of the skin according to the ISO 9886 standard [57]. The underarm-finger skin temperature gradient indicates vasoconstriction [58]. Therefore, two additional iButtons were placed at the underarm and the middle finger. A chest belt (H10, Polar, RR interval detection accuracy is 99.6% [59]) was used to continuously assess heart rate and heart rate variability (pNN50). The representative values of skin temperature and heart rate measures were calculated as the mean values during the 10-min interval before the submission of the questionnaire.

The respiration chamber (Omnical, Maastricht Instruments, accuracy: ±2%) gas analyzer was used to obtain data on energy expenditure, carbohydrate oxidation and lipid oxidation based on Weir's equation [60] and Massicotte's formulas [61]. Physical activity was gauged by an acceleration meter attached to the thigh (MOX, Maastricht Instruments). The data of the respiration chamber measures and physical activity were averaged per 20 min.

Hand skin blood flow was probed by a Laser Doppler Flowmetry (PF5000, Perimed AB) attached on the dorsal side of the left hand. A relative value (the values in Periods 1 and 2 divided by the values in Period 0) was calculated because the Laser Doppler Flowmetry measures the relative value of the blood flow rather than absolute blood flow. Since the blood flow measurement is sensitive to movements, the participants were instructed to not move for 3 min during the blood flow measurements. Therefore, the average value over these 3 min was used for hand skin blood flow.

Blood pressure was measured three times at the end of each period using a blood pressure monitor (HEM-7322U-E, OMRON, accuracy: ±3 mmHg, range: 0–229 mmHg). The three blood pressure measurements were averaged per period.

2.3.5. *Cognitive tasks and task questionnaire*

Four cognitive tasks were used to assess four cognitive processes related to office activities. The Hampshire tree task tested for *planning ability,* the grammatical reasoning task for *verbal ability*, the digital span task for *working memory* and the spatial rotation task for *mental spatial manipulation*. Those four tasks have been validated and are from classical psychological paradigms [62]. Detailed information for these four tasks can be found in the reference [62]. The standardized scores of these four tasks were averaged to obtain a *comprehensive performance score*.

The task questionnaire measured the perceived task demands (physical demand, mental demand and temporal demand) and self-perceptions of performance, effort, frustration level and motivation. Those parameters were measured by the classical NASA task load index questionnaire [63] (Fig. S5a), except for motivation, for which the scale was adopted from Cui et al. [64] (Fig. S5b).

2.4. *Statistical tests*

Extreme outliers were excluded for the cognitive tasks, where scores exceeding four times the standard deviation from the population mean were labelled as extreme outliers [62].

The sleep questionnaire data were analyzed to check whether participants complied with the sleep instructions (results *Section 3.1*). Mixed-effects models were used to test whether there were differences in sleep parameters between the scenarios. The participant was added as a random intercept and the scenario was included as a fixed factor.

To investigate the effects of antecedent CCT in Period 1 on preferred CCT in Period 2 (results *Section 3.2*), paired t-tests were used to compare the preferred CCT between the two personal control scenarios: antecedent CCT of 2700 K vs. antecedent CCT of 5700 K.

Mixed-effects models were used to examine the effects of personal control of CCT (results *Section 3.3)*. For this, only the data of Period 2, where personal control was granted or withheld, were analyzed. Separate analyses were conducted for the two scenarios that started in 2700 K from those starting in 5700 K. The participant was included as a random intercept to consider the repeated measures. The personal control of CCT (Yes/No), the timepoints as a categorical variable, and their interactions were treated as fixed factors. Since the air temperature differed slightly (17.2 ± 0.3 °C) from the designed air temperature, the measured air temperature was also included as a fixed factor. Furthermore, baseline measurement at the end of Period 1 ($t = 60$ min), age, sex, day timing, the order of the scenarios, body surface area to mass ratio (heat loss ability [65]), and fat-free mass to body surface ratio (heat production ability [65]) were added as covariates in the models of personal control to account for variance explained in the outcome parameters by these variables. Only significant covariates were kept in the model using a 'top-down' modelling strategy [66]. In the case of post-hoc comparisons per timepoint, the p-values were corrected according to the false discovery rate method. Cohen's *d* for the main effect of personal control was calculated based on the method from Westfall et al. [67]. To compare the variances in light color preference between no-control and personal-control scenarios, the data were averaged per participant, per scenario. Levene's test was used to test the differences between variances.

Additional exploratory analyses were done to test the psychological and personalization effects of personal control (having control and having exercised it to tune settings to personal preference), together with the effect of actual CCT (results *Section 3.4)*. For this analysis, mixed-effects models were run with the pooled data of four scenarios. The participant was added as a random intercept. Personal control (Yes/No), the timepoints as a categorical variable and the actual CCT participants experienced in Period 2 were added as fixed factors. Similarly, the air temperature was included. The baseline measurement at the end of Period 1 ($t = 60$ min) was treated as a fixed factor to consider the baseline differences induced by the antecedent CCT. Identical to the analyses in *Section 3.3*, the same covariates except for the baseline were examined using a 'top-down' modelling strategy. Cohen's f^2 was reported to evaluate the effect sizes of having and exercising control as well as actual CCT according to Selya et al.'s method [68].

Assumptions of mixed-effects models were checked. The effects of the predictors in the final mixed-effects models were examined using conditional F-tests with the Kenward-Roger's correction of degrees of freedom [69]. The mixed-effects model analyses were performed using open-source software packages in R 4.2.0 (LmerTest package [69], Emmeans package [70]). A cut-off value for p of 0.05 was used to test for significance.

3. Results

3.1. High compliance of participants to sleep instructions before test days

The analyses on sleep questionnaires revealed that participants' bed times and sleep duration did not significantly differ among four scenarios (all $p > 0.1$). The average time they went to bed was 23:43, the average time they got up was 7:54, and the average sleep duration was 7.5 h. These findings suggest that participants complied with sleep instructions before the test days.

3.2. Participants' control behavior

The antecedent CCT in Period 1 significantly affected preferred CCT in Period 2 (Fig. 2a). Pre-exposure to 2700 K resulted in a lower preferred CCT compared to pre-exposure to 5700 K (antecedent CCT 2700 K vs. 5700K: 3280 ± 1101 vs. 4297 ± 944 K, $p < 0.001$, $d = 1.1$, Fig. 2b). Visual inspection suggests large interpersonal variation existed in the effects of antecedent CCT on preferred CCT. Some participants were consistent in their light preference (individuals with flat slopes in Fig. 2b), whereas other participants' preference for CCT substantially depended on the CCT in the first period (individuals with steep slopes in Fig. 2b). Overall, 10 of 16 participants adjusted their light when the antecedent CCT was 2700 K, while 12 of 16 participants changed the light with an antecedent CCT of 5700 K.

3.3. The effects of personal control of CCT

The interactions between personal control of CCT and timepoints were insignificant for all the outcome parameters (all $p > 0.05$), indicating that the effects of personal control of CCT did not significantly depend on the time in Period 2. Therefore, for the following analyses in this section, we focused on reporting by-scenario data (average over time points) and the main effects of personal control. The detailed over-time data is shown in the supplementary materials, Figs. S6–S13. For the interest of how outcome parameters developed over time (main effects of time), readers are referred to our previous paper (the same protocol) regarding the effects of CCT over 140-min exposure [20]. In this section, the data are consistently reported as no control scenario (NC) vs. personal control scenario (PC) with estimated marginal means ± standard error, unless stated otherwise. P value and Cohen's d for the main effects of personal control was also reported.

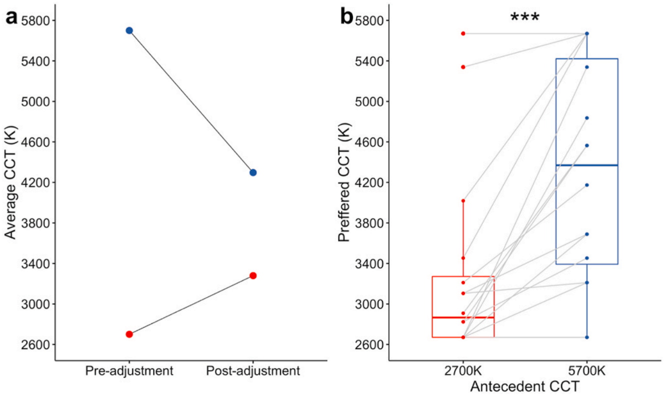

Fig. 2. Effects of the antecedent CCT in Period 1 on the preferred CCT in Period 2; a) average CCT for pre-adjustment and post-adjustment; b) detailed comparison of preferred CCT between two antecedent CCTs. The grey lines represent the preferred CCT of specific individuals. *** indicates $p < 0.001$.

3.3.1. Visual perceptions

After personal control, the light color sensations were closer to 'neutral' color sensation in both antecedent CCT conditions (antecedent 2700 K: 0.74 ± 0.16 (NC) vs. 0.16 ± 0.16 (PC), $p < 0.001$, $d = 0.70$; antecedent 5700 K: −1.30 ± 0.18 (NC) vs. −0.07 ± 0.18 (PC), $p < 0.001$, $d = 1.20$; Fig. 3a). In contrast, personal control only significantly affected light color preference when the antecedent CCT was 5700 K (−0.64 ± 0.06 (NC) vs. 0.06 ± 0.06 (PC), $p < 0.001$, $d = 1.32$). For antecedent CCT of 2700 K, the light color preference was already close to 'neutral' without personal control and personal control of CCT did not significantly influence light color preference (−0.11 ± 0.06 (NC) vs. −0.02 ± 0.06 (PC), $p = 0.153$, $d = 0.24$; Fig. 3b). In addition, the variance in light color preferences was significantly smaller in the personal control scenario compared to the no control scenario with antecedent CCT of 5700K (Levene's test, $p = 0.014$), indicating that personal control successfully addressed individual differences in terms of color preference.

Similarly, the illuminance sensation was closer to neutral after personal control with an antecedent CCT of 5700 K (0.95 ± 0.10 (NC) vs. 0.59 ± 0.10 (PC), $p < 0.001$, $d = 0.48$, Fig. 3c). In contrast, with an antecedent CCT of 2700 K, illuminance sensation was further away from the neutral illuminance sensation after personal control (0.14 ± 0.12 (NC) vs. 0.43 ± 0.12 (PC), $p < 0.001$, $d = 0.73$, Fig. 3c). Light illuminance preference showed a similar pattern as light illuminance sensation (antecedent 2700K: −0.05 ± 0.07 (NC) vs. −0.18 ± 0.07 (PC), $p = 0.017$, $d = 0.36$; antecedent 5700 K: −0.54 ± 0.08 (NC) vs. 0.15 ± 0.08 (PC), $p < 0.001$, $d = 0.93$; Fig. 3d).

Personal control of CCT substantially improved visual comfort in both antecedent CCTs (antecedent 2700 K: 0.67 ± 0.12 (NC) vs. 1.10 ± 0.12 (PC), $p < 0.001$, $d = 0.69$; antecedent 5700 K: 0.43 ± 0.09 (NC) vs. 1.51 ± 0.09 (PC), $p < 0.001$, $d = 1.59$; Fig. 3e). In line, participants appraised the light as more visually pleasant in the personal control scenarios (antecedent 2700 K: 0.58 ± 0.13 (NC) vs. 1.04 ± 0.13 (PC), $p < 0.001$, $d = 0.60$; antecedent 5700 K: 0.27 ± 0.15 (NC) vs. 1.52 ± 0.15 (PC), $p < 0.001$, $d = 1.37$; Fig. 3f).

3.3.2. Eye-related symptoms

Eye strain was significantly mitigated by allowing personal control in both antecedent CCT conditions (antecedent 2700 K: 1.74 ± 0.12 (NC) vs. 1.36 ± 0.12 (PC), $p < 0.001$, $d = 0.66$; antecedent 5700 K: 1.51 ± 0.14 (NC) vs. 1.37 ± 0.14 (PC), $p = 0.023$, $d = 0.23$; Fig. 4a). Similarly, personal control of CCT reduced eye discomfort (antecedent 2700 K: 1.74 ± 0.10 (NC) vs. 1.29 ± 0.10 (PC), $p < 0.001$, $d = 0.88$; antecedent 5700 K: 1.57 ± 0.09 (NC) vs. 1.19 ± 0.09 (PC), $p < 0.001$, $d = 0.74$; Fig. 4b) and eye fatigue (antecedent 2700 K: 1.82 ± 0.10 (NC) vs. 1.35 ± 0.10 (PC), $p < 0.001$, $d = 0.92$; antecedent 5700 K: 1.57 ± 0.10 (NC) vs. 1.44 ± 0.10 (PC), $p = 0.042$, $d = 0.26$; Fig. 4c). Overall, the mean votes of eye-related symptoms were less than 'slight' at all time points in all scenarios (Fig. S6 g-i).

3.3.3. Thermal perceptions

Personal control of CCT did not significantly affect whole-body thermal sensation (antecedent 2700 K: $d = 0.09$, $p = 0.530$; antecedent 5700 K: $d < 0.01$, $p = 0.997$, Fig. 5a) and thermal comfort

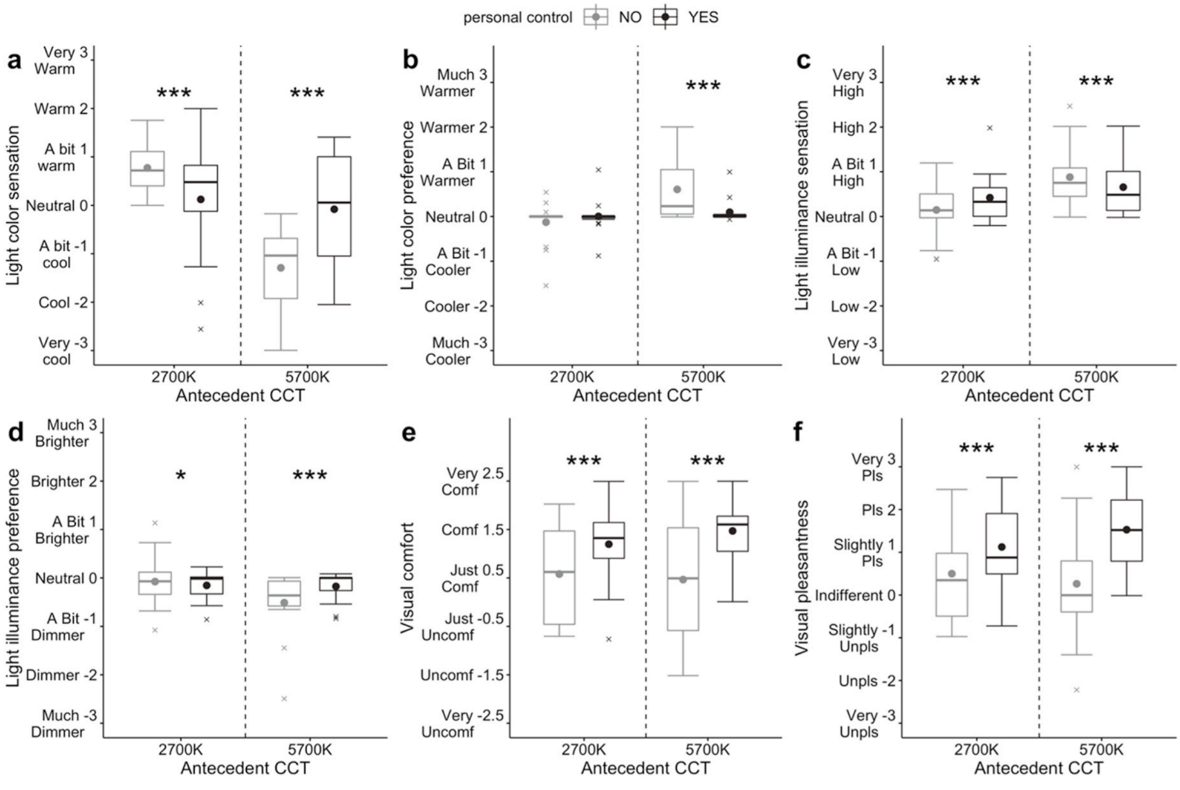

Fig. 3. By-scenario visual perceptions: a) light color sensation, b) light color preference, c) light illuminance sensation, d) light illuminance preference, e) visual comfort, f) visual pleasantness. The symbol *, ** and *** indicate $p < 0.05$, $p < 0.01$, $p < 0.001$, respectively, and x indicates potential outliers.

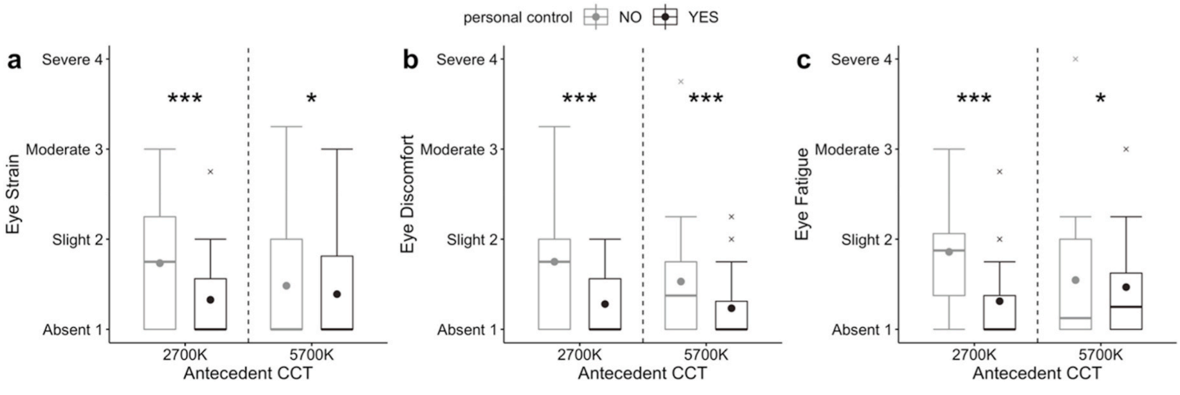

Fig. 4. By-scenario eye-related symptom: a) eye strain, b) eye discomfort, c) eye fatigue. The symbol *, ** and *** indicate $p < 0.05$, $p < 0.01$, $p < 0.001$, respectively, and x indicates potential outliers.

(antecedent 2700 K: d = 0.06, p = 0.670; antecedent 5700 K: d = 0.06, p = 0.623, Fig. 5b). In line, it also did not significantly influence thermal preference (antecedent 2700 K: d = 0.09, p = 0.530; antecedent 5700 K: d = 0.12, p = 0.378, Fig. S7c) and thermal pleasantness (antecedent 2700 K: d = 0.06, p = 0.687; antecedent 5700 K: d < 0.01, p = 0.952, Fig. S7d). Perceived shivering was increased by personal control with pre-exposure to 5700 K (0.49 ± 0.08 (NC) vs. 0.67 ± 0.08 (PC), p = 0.011, d = 0.40, Fig. 5c), but it did not significantly respond to personal control when antecedent CCT was 2700 K (0.77 ± 0.11 (NC) vs. 0.72 ± 0.11 (PC), p = 0.484, d = 0.09, Fig. 5c).

Thermal acceptance rates were rather similar among the four scenarios (antecedent 2700 K: 78.1% (NC), 73.4% (PC); antecedent 5700 K: 79.7% (NC) and 78.1% (PC)). Thermal comfort rates (the percentage of the votes equal or higher than 'just comfortable') were also close to each other between the no control and personal control scenarios (antecedent 2700 K: 28.1% (NC) vs. 25% (PC); antecedent 5700 K: 42.2% (NC) vs. 37.5% (PC).

3.3.4. Physiological parameters

Energy expenditure was significantly higher in the personal control scenario than in the no control scenario with antecedent CCT of 2700 K (5.47 ± 0.07 (NC) vs. 5.62 ± 0.07 (PC) kJ/min, p = 0.014, d = 0.42, Fig. 6.a). No significant difference in energy expenditure was found with pre-exposure to 5700 K (5.53 ± 0.07 (NC) vs. 5.50 ± 0.07 (PC) kJ/min, p = 0.533, Fig. 6.a). In addition, when antecedent CCT was 5700 K, personal control increased heart rate by 1.2 bpm (71.70 ± 0.56 (NC) vs. 72.90 ± 0.56 (PC) bpm, p = 0.002, d = 0.42, Fig. 6.b) and decreased heart rate variability (pNN50) by 2.4% (26.8% ± 2.4 (NC) vs. 24.4% ± 2.4 (PC), p = 0.004, d = 0.23, Fig. 6.c) compared to no control.

Mean skin temperature, finger-underarm skin temperature gradient, hand skin blood flow, carbohydrate and lipid oxidation, and blood pressures were not significantly responsive to personal control in both

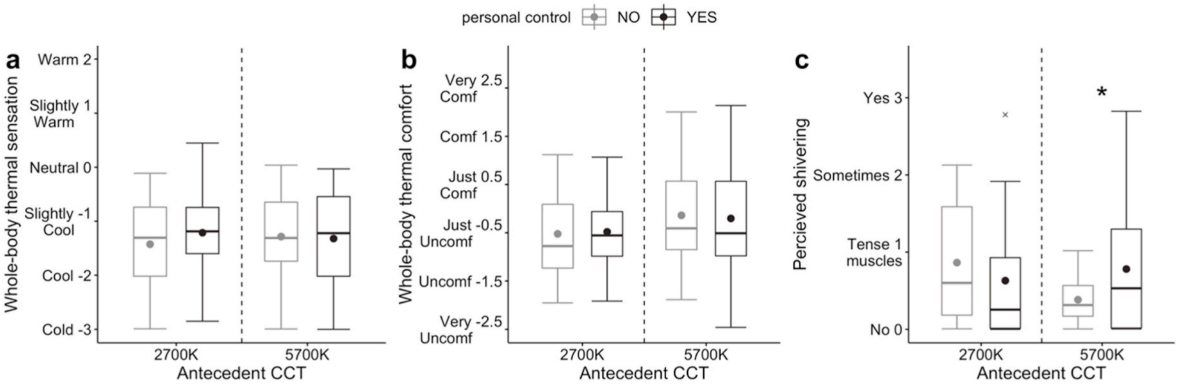

Fig. 5. By-scenario thermal perceptions: a) thermal sensation; b) thermal comfort; c) perceived shivering. The symbol *, ** and *** indicate $p < 0.05$, $p < 0.01$, $p < 0.001$, respectively, and x indicates potential outliers.

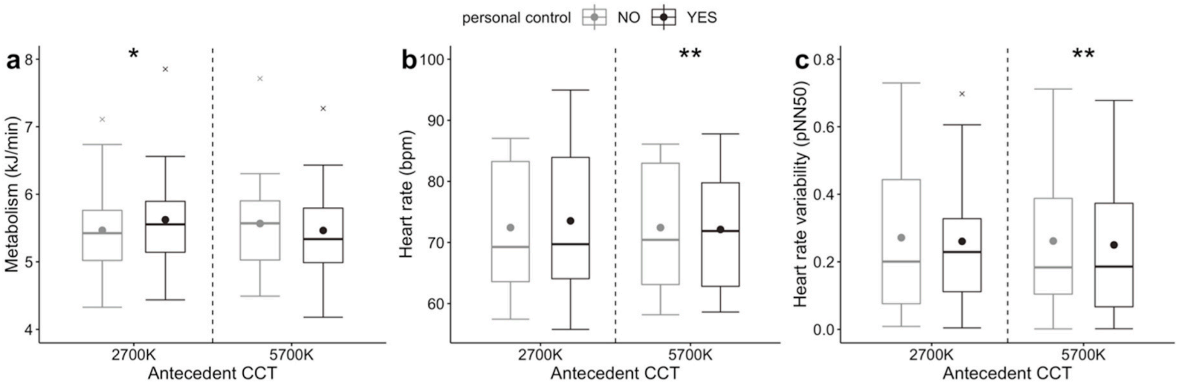

Fig. 6. By-scenario physiological responses with antecedent 2700 K (left) and 5700K (right): a) energy expenditure, b) heart rate, c) heart rate variability. The symbol *, ** and *** indicate $p < 0.05$, $p < 0.01$, $p < 0.001$, respectively, and x indicates potential outliers.

antecedent CCT conditions (Figs. S8a–j).

3.3.5. *Local body response*

Local body skin temperature, local thermal sensation and local thermal comfort at $t = 130$ did not significantly differ between no control and personal control scenarios with both antecedent CCTs, including head, neck, upper arm, lower arm, hands, torso, thigh, calf and feet (Fig. S9).

3.3.6. *Cognitive performance*

When the antecedent CCT was 5700 K, personal control significantly improved performance on the grammatical reasoning task (21.4 ± 1.0 (NC) vs. 23.2 ± 1.0 (PC), $p = 0.052$, $d = 0.35$, Fig. 7.a) and spatial planning task (62.9 ± 2.0 (NC) vs. 67.2 ± 2.0 (PC), $p = 0.046$, $d = 0.37$, Fig. 7.b). However, the performance on the rotation task decreased by personal control (148.0 ± 6.4 (NC) vs. 123.0 ± 6.9 (PC), $p = 0.011$, $d = 0.58$, Fig. 7.c). No significant differences between control and no control were found in these task performances with antecedent CCT of 2700 K (all $p > 0.05$, Fig. 7.). Moreover, digital span and comprehensive task scores were similar between no control and personal control scenarios after both antecedent CCTs (all $p > 0.05$, Figs. S10b and e).

3.3.7. *Task questionnaire*

Regarding subjective perceptions of workload, personal control

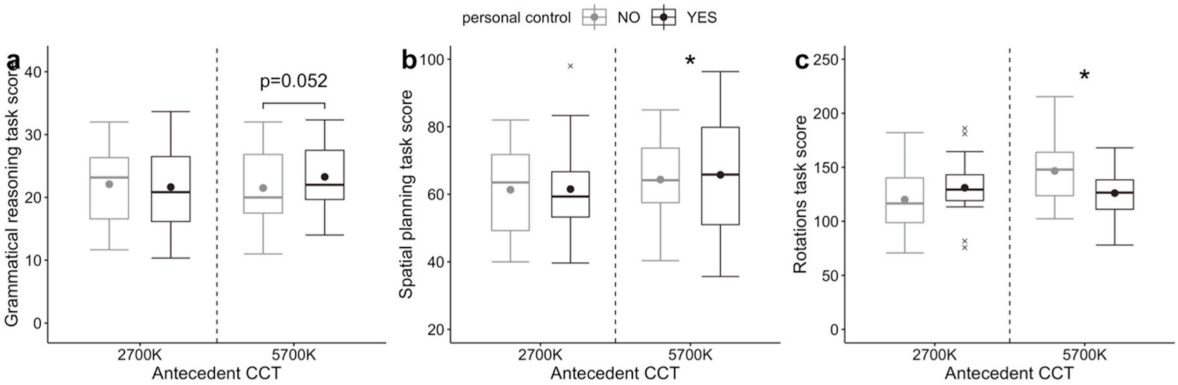

Fig. 7. By-scenario cognitive task performance: a) grammatical reasoning task, b) spatial planning task, c) rotation task. The symbol *, ** and *** indicate $p < 0.05$, $p < 0.01$, $p < 0.001$, respectively, and x indicates potential outliers.

significantly decreased perceived mental demand of the tasks when antecedent CCT was 5700 K (66.1 ± 2.3 (NC) vs. 60.5 ± 2.3 (PC), $p < 0.001$, $d = 0.53$, Fig. 8.a). There was no statistically significant effect in the 2700 K CCT antecedent conditions ($p = 0.185$, Fig. 8.a). Personal control of CCT did not significantly affect physical demand and temporal demand (all $p > 0.05$, Figs. S11b and c) after either antecedent condition.

Participants did not perceive significant differences in performance on, effort investments in, frustration level with, or motivation for cognitive tasks between control condition in either antecedent CCT condition (all $p > 0.05$, Fig. S12).

3.3.8. *Alertness, pleasure and arousal*

Participants felt more alert (less sleepy) in the personal control scenario with antecedent CCT of 5700 K (4.51 ± 0.19 (NC) vs. 4.04 ± 0.19 (PC), $p < 0.001$, $d = 0.48$, Fig. 8.b). However, this significant effect did not emerge with antecedent CCT of 2700 K (4.88 ± 0.14 (NC) vs. 4.62 ± 0.14 (PC), $p = 0.068$, $d = 0.29$, Fig. 8.b). No statistically significant effects of personal control were found on arousal (antecedent CCT 2700 K: 4.24 ± 0.20 (NC) vs. 4.49 ± 0.20 (PC), $p = 0.080$, $d = 0.24$; antecedent CCT 5700 K: 4.71 ± 0.06 (NC) vs. 4.65 ± 0.20v (PC), $p = 0.693$, $d = 0.05$; Fig. 8.c). In addition, pleasure was not significantly affected by personal control (antecedent CCT 2700 K: 5.32 ± 0.16 (NC) vs. 5.51 ± 0.16 (PC), $p = 0.278$, $d = 0.19$; antecedent CCT 5700 K: 5.79 ± 0.13 (NC) vs. 6.07 ± 0.13 (PC), $p = 0.068$, $d = 0.31$; Fig. S13b).

3.4. *The psychological and personalization effects of personal control vs. actual CCT in Period 2*

To investigate the psychological and personalization effects of personal control (i.e., having control and having exercised it to tune settings to personal preference) vis-a-vis the effects of the objective light conditions, we added the actual CCT in Period 2 to the models exploring effects of control condition, using pooled data of four scenarios (note: these models also included the actual CCT level that was set or selected). All results (coefficients ± standard errors and p values) in this section are reported in Table 1, unless stated otherwise. Cohen's f^2 for the effects of having and exercising control as well as actual CCT were reported.

3.4.1. *Visual perception outcomes*

Most visual perception outcomes and eye-related symptoms were positively influenced by having and exercising control, except for light color and illuminance sensations. Having and exercising control significantly improved visual comfort ($p < 0.001$, $f^2 = 0.26$), boosted visual pleasantness ($p < 0.001$, $f^2 = 0.24$), decreased preference for a warmer color ($p < 0.001$, $f^2 = 0.07$) and increased preference for a higher illuminance ($p = 0.034$, $f^2 = 0.01$). On the other hand, over and above the effects of 'having and exercising control', a higher CCT resulted in a significantly cooler color sensation ($f^2 = 0.69$), a higher preference for a warmer light color ($f^2 = 0.07$), a brighter illuminance sensation ($f^2 = 0.04$), and a lower preference for higher illuminance ($f^2 = 0.06$, all $p < 0.001$). No significant associations between actual CCT and visual comfort and visual pleasantness were found.

3.4.2. *Eye-related symptoms*

Eye-related symptoms were significantly mitigated by having and exercising control, including eye strain ($f^2 = 0.07$), eye discomfort ($f^2 = 0.18$) and eye fatigue ($f^2 = 0.08$, all $p < 0.001$). In contrast, actual CCT did not significantly affect eye-related symptoms.

3.4.3. *Thermal perception outcomes*

Having and exercising control had no significant effects on thermal sensation, comfort, preference, pleasantness and perceived shivering. Higher actual CCT, however, did significantly improve thermal comfort ($p = 0.009$, $f^2 = 0.01$), increased thermal pleasantness ($p = 0.019$, $f^2 = 0.01$), lowered preference for warmth ($p = 0.011$, $f^2 = 0.02$) and had less perceived shivering ($p < 0.001$, $f^2 = 0.01$), although it did not significantly influence thermal sensation.

3.4.4. *Physiological outcomes*

By having and exercising control, heart rate was increased ($p = 0.004$, $f^2 = 0.03$) and heart rate variability was decreased ($p = 0.009$, $f^2 = 0.05$). However, other physiological outcomes did not significantly respond to having and exercising control. Furthermore, actual CCT had no significant effects on all physiological outcomes.

3.4.5. *Cognitive performance outcomes*

No significant effects of having and exercising control were found on the performance on cognitive tasks. Notably though, the digital span ($f^2 = 0.07$), rotation ($f^2 = 0.04$) and comprehensive task scores ($f^2 = 0.05$) were enhanced by higher CCT (all $p < 0.05$).

3.4.6. *Task questionnaire outcomes*

By having and exercising control, self-perceived performance was improved ($p = 0.021$, $f^2 = 0.03$) and the perception of mental demand of the tasks decreased ($p < 0.001$, $f^2 = 0.05$). Having and exercising control did not significantly affect physical demand, temporal demand, effort investments, frustration level and motivation. For the effects of CCT, higher CCT led to higher temporal demand ($p < 0.001$, $f^2 = 0.08$). However, no significant effects of CCT were found on other task questionnaire outcomes.

3.4.7. *Alertness, pleasure and arousal*

Having and exercising control significantly boosted alertness ($p < 0.001$, $f^2 = 0.02$) and pleasure ($p = 0.014$, $f^2 = 0.01$). For arousal, this effect did not reach significance ($p = 0.099$). On the other hand, higher

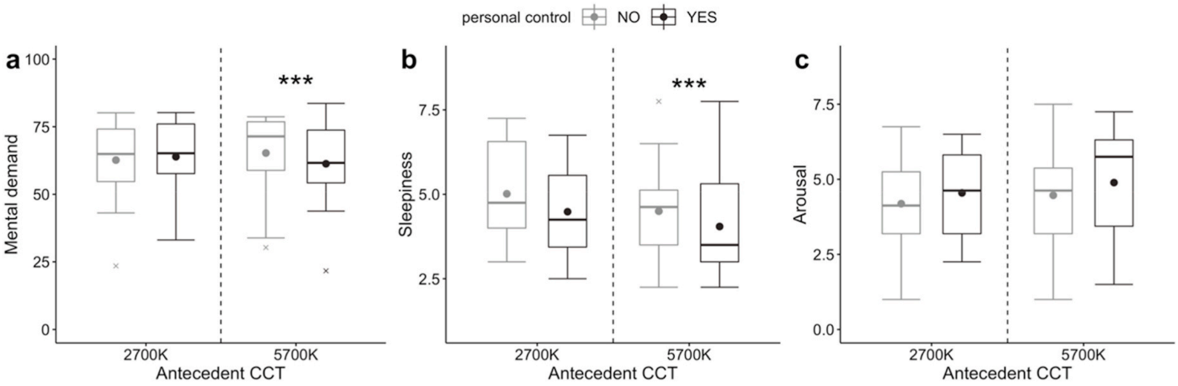

Fig. 8. By-scenario subjective responses: a) mental demand, b) sleepiness, c) arousal. The symbol *, ** and *** indicate $p < 0.05$, $p < 0.01$, $p < 0.001$, respectively, and x indicates potential outliers.

Table 1
Parameter estimates for the effect of having and exercising control as well as the effect of actual CCT on all outcome measures.

Outcomes	Having and exercising control		Actual CCT	
	Coefficient ±standard error	p value	Coefficient ±standard error	p value
Visual perceptions				
Color sensation	0.016 ± 0.090	0.859	**−0.692 ± 0.051**	**<0.001**
Color preference	**−0.189 ± 0.050**	**<0.001**	**0.110 ± 0.023**	**<0.001**
Illuminance sensation	0.049 ± 0.054	0.366	**0.159 ± 0.025**	**<0.001**
Illuminance preference	**0.093 ± 0.043**	**0.034**	**−0.074 ± 0.018**	**<0.001**
Visual comfort	**0.764 ± 0.076**	**<0.001**	−0.013 ± 0.030	0.664
Visual pleasantness	**0.882 ± 0.097**	**<0.001**	−0.023 ± 0.038	0.556
Eye-related symptoms				
eye strain	**−0.288 ± 0.050**	**<0.001**	−0.032 ± 0.021	0.128
eye discomfort	**−0.414 ± 0.054**	**<0.001**	−0.027 ± 0.022	0.222
eye fatigue	**−0.312 ± 0.054**	**<0.001**	−0.035 ± 0.022	0.116
Thermal perceptions				
Thermal sensation	0.083 ± 0.067	0.215	0.044 ± 0.026	0.091
Thermal comfort	0.028 ± 0.069	0.683	**0.077 ± 0.029**	**0.009**
Thermal preference	−0.032 ± 0.061	0.598	**−0.063 ± 0.025**	**0.011**
Thermal pleasantness	0.042 ± 0.073	0.563	**0.070 ± 0.030**	**0.019**
Perceived shivering	0.054 ± 0.052	0.299	**−0.082 ± 0.022**	**<0.001**
Physiology				
Mean skin temperature	−0.009 ± 0.014	0.532	−0.002 ± 0.006	0.785
Underarm-finger gradient	0.170 ± 0.169	0.316	0.045 ± 0.067	0.509
Metabolism	0.065 ± 0.040	0.104	0.011 ± 0.016	0.497
Carbohydrate oxidation	0.002 ± 0.007	0.738	−0.002 ± 0.003	0.581
Lipid oxidation	<0.001 ± 0.003	0.991	0.001 ± 0.001	0.563
Hand skin blood flow	0.010 ± 0.020	0.626	0.004 ± 0.008	0.634
Heart rate	**0.810 ± 0.280**	**0.004**	0.014 ± 0.114	0.901
Heart rate variability	**−0.018 ± 0.007**	**0.009**	0.001 ± 0.003	0.698
Systolic blood pressure	−0.771 ± 1.076	0.478	−0.289 ± 0.424	0.500
Diastolic blood pressure	−0.975 ± 0.733	0.190	0.149 ± 0.282	0.599
Cognitive performance				
Grammatical reasoning task	0.473 ± 0.586	0.421	−0.036 ± 0.243	0.882
Digital span task	0.044 ± 0.125	0.724	**0.120 ± 0.050**	**0.018**
Spatial planning task	1.266 ± 1.587	0.426	0.733 ± 0.642	0.255
Rotation task	−0.066 ± 0.142	0.643	**0.142 ± 0.055**	**0.011**
Comprehensive task index	−0.004 ± 0.239	0.985	**0.237 ± 0.095**	**0.014**
Task questionnaire				
Mental demand	**−3.419 ± 0.987**	**0.001**	0.635 ± 0.388	0.103
Physical demand	−0.038 ± 1.244	0.976	0.493 ± 0.497	0.323
Temporal demand	0.607 ± 1.526	0.691	**2.176 ± 0.594**	**<0.001**
Perceived performance	**4.384 ± 1.887**	**0.021**	0.426 ± 0.773	0.582
Effort investments	−0.265 ± 1.272	0.835	0.706 ± 0.518	0.174
Frustration level	−0.492 ± 1.907	0.797	0.066 ± 0.748	0.929
Motivation	0.176 ± 0.117	0.135	0.059 ± 0.048	0.217
Other subjective perceptions				
Sleepiness (alert)	**−0.408 ± 0.098**	**<0.001**	−0.055 ± 0.041	0.185
Pleasure	**0.296 ± 0.120**	**0.014**	**0.157 ± 0.047**	**<0.001**
Arousal	0.181 ± 0.110	0.099	**0.147 ± 0.044**	**<0.001**

Note: Significant effects are shown in **bold**. The coefficients for CCT are scaled by multiplying 1000.

CCT increased pleasure ($p < 0.001$, $f^2 = 0.05$), and arousal ($p < 0.001$, $f^2 = 0.04$), but did not significantly affect alertness ($p = 0.185$).

4. Discussion

This study investigated the effects of personal control of CCT on visual appraisals, thermal appraisals, affect and cognitive performance. As expected, the personal control of CCT positively influenced visual appraisals and mitigated eye-related symptoms compared to no-control scenarios for both antecedent CCT conditions. However, no statistically significant effects of personal control of CCT were found on thermal appraisals. For other outcome parameters, most significant differences were found only when the antecedent CCT was 5700 K, where personal control of CCT differentially affected task performance, and reduced subjective mental demand and sleepiness. In addition, exploratory analyses also support the finding that having and exercising control improve visual comfort and eye-related symptoms, but not thermal comfort. Task performance was not significantly affected by having and exercising control, but having and exercising control may reduce mental demands, and increase self-perceived performance, pleasure and alertness. In addition, the effects of the actual CCT setting did influence thermal perceptions and cognitive performance and largely replicated findings reported earlier [20]. Readers are referred to our previous paper for the discussion on the effects of actual CCT [20].

4.1. *Can thermal discomfort be mitigated via increasing visual comfort?*

The current study is one of the first to explicitly investigate if improvements in visual comfort can improve thermal comfort via personal control of CCT (maximizing visual comfort). We found that personal control of CCT indeed substantially improved visual comfort. However, the main analyses suggest that this improvement on visual comfort did not occur for thermal comfort under mild cold conditions (17 °C). In line, exploratory analyses also showed that having and exercising control over CCT did not significantly ameliorate the aversive effects of mild cold on thermal comfort, despite the fact that it boosted visual comfort. Therefore, our findings do not support the hypothesis that having control over sensory input in the visual domain can impact appraisals in the thermal domain, although it has been advocated that having control over one negative stimulus may help reduce or ameliorate the negative effects of another negative stimulus [30–32].

When these null effects are observed, one might argue that perhaps the sample size was too small to detect the effects. Although this explanation cannot be conclusively eliminated, it is unlikely to be the case. In te Kulve's study [7], a significant visual-thermal comfort association was established using four light settings and 16–19 participants per lighting setting (mixed with within- and between-subject designs) in cold conditions (PMV ~ = −2.2). This is comparable to our study, which collected data from four lighting scenarios and 16 participants per lighting scenario (within-subject design) at 17 °C (PMV ~ = −1.65). Moreover, we explored which effect size could be detected with sufficient power given the current number of participants, the observations nested within participants and the study design. Ten thousand Monte Carlo simulations were run to obtain sensitivity-power curves using the simr package [71] according to Brysbaert's paper [72]. The sensitivity-power curves (Fig. 9) show that this study has at least 80% statistical power to detect an effect that is larger than 0.27 units on a six-point comfort scale. Considering that 0.27 units on a six-point comfort scale is a rather small effect, this again supports that our study design had sufficient accuracy to detect the effects of personal control of CCT on thermal comfort with 80% statistical power.

A more likely explanation is that the association between thermal comfort and visual comfort may derive from a causal path running from thermal comfort to visual comfort, but not vice versa. For example, te Kulve et al. [7] investigated visual comfort and thermal comfort in different lighting and thermal conditions. In their study, visual comfort was higher in thermoneutral conditions (thermally most comfortable) than in non-neutral conditions. However, the lighting condition did not affect thermal comfort. In line, Yang et al. [73] also found that air temperature can affect visual comfort. The highest visual comfort appeared in the thermal conditions that manifested in the highest thermal comfort. However, the highest thermal comfort did not always appear in the illuminance condition that was perceived as most comfortable [73]. Nevertheless, more evidence is needed to verify the causal path from thermal comfort to visual comfort. As large individual variation also exists in thermal comfort [74,75], it is recommended to investigate the effects of personal control of temperature on visual comfort in future studies.

4.2. *Personal control of CCT improves visual appraisals and eye-related symptoms*

This study intended to use personal control of CCT to address individual differences, thereby improving visual comfort. As expected, when the antecedent CCT was 5700 K, the mean light color preference came closer to 'no change' and its variance was reduced by using the personal control. This suggests that the designed personal lighting system successfully addressed individual differences in light color preference. In line, personal control over CCT improved the visual appraisals and mitigated eye-related symptoms. These findings corroborate other studies suggesting that personal control over illuminance benefits visual appraisals [33–35]. Interestingly, the light illuminance sensation and preference were also affected by personal control of CCT, although actual illuminances were fixed during the experiment. A plausible explanation is that brightness sensation is positively related to CCT, as observed in our previous study [20] and others [18,25,76,77].

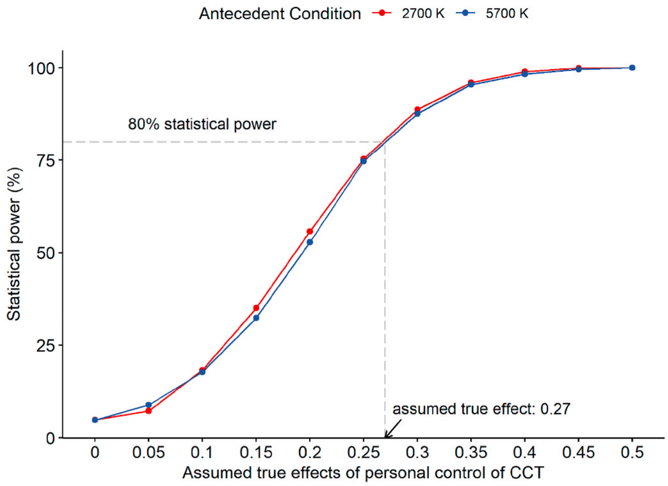

Fig. 9. Sensitivity power analysis: Statistical power vs. assumed true effects of personal control of CCT on thermal comfort.

Further exploratory analyses revealed an interesting pattern on visual appraisals and eye-related symptoms. After controlling for the actual CCT, having and exercising control was associated with improved visual appraisals and mitigated eye-related symptoms but not with light color and illuminance sensation. A possible explanation is that light color and illuminance sensations are more likely to be sensory detections of the light, while visual comfort, pleasantness and preference are more individual evaluations of the light that have substantial interindividual differences. Giving personal control therefore benefits these appraisals.

4.3. *Does personal control of CCT benefit cognitive performance?*

Baron's positive affect theory [78,79] suggests that personal control can lead to preferred conditions that create a positive affect state, and therefore, improve performance. In the current study, most performance-related effects of personal control only appeared with the antecedent CCT of 5700 K. When the antecedent CCT was 5700 K (a setting not preferred by most), the personal control tended to increase pleasure, although not significantly so ($p = 0.068$). Meanwhile, it significantly improved performance on the grammatical reasoning and spatial planning task, however, it decreased performance on the rotation task. One possible reason is that the actual CCT differentially affects performance on different tasks. Our exploratory analysis showed that higher CCT enhanced performance on the rotation task, whereas performance for the grammatical reasoning and spatial planning tasks was unaffected by the CCT. This finding is also consistent with our previous study [20] and other studies that show CCT differentially affects different types of cognitive tasks [80,81]. Therefore, lower actual CCT in the personal control scenario may have decreased the performance on the rotation task. On the other hand, obtaining one's preferred condition may have improved performance on grammatical reasoning and spatial planning tasks via affective, motivational pathways, as previous literature suggested [78,79,82].

How personal control of CCT affects participants' perceptions of the tasks also has practical implications for the workplace. When the antecedent CCT was 5700 K, our results indicate that personal control of CCT reduced mental demand and enhanced alertness. In addition, although its effects on subjective arousal were not significant, personal control of CCT increased heart rate and decreased heart rate variability, which is in some studies associated with higher physiological arousal [83,84]. Similarly, the exploratory analysis (Table 1) also suggested that having and exercising control decreases perceived mental demand, and boosts alertness, pleasure, perceived performance, and physiological arousal. Although effect sizes were generally modest, these results generally suggest that giving workers personal control benefits their perceptions of the tasks.

4.4. *Practical implications*

The common view of personal control is that personal control benefits comfort, affect and productivity. In this study, we indeed revealed benefits of personal control of CCT, especially for visual appraisals and eye-related symptoms, i.e., appraisals in the visual domain. However, we also observed, surprisingly, a negative effect on the rotation task performance with an antecedent CCT of 5700 K. It suggests that by giving personal control, people may steer towards more comfort, while these preferred conditions may not be optimal for cognitive processes related to mental spatial manipulation (the rotation task). Nevertheless, on average, the comprehensive task performance was not significantly affected by the personal control of CCT. Together, these findings imply that the deployment of personal control of CCT is generally beneficial, although care needs to be taken when the primary interest is the cognitive performance related to mental spatial manipulation.

In addition, the antecedent CCT significantly affected participants' preferred CCT. In particular, we saw that individuals selected higher CCT values after initial exposure to a higher CCT condition. This finding is also consistent with de Korte et al. [85], who reported that the pre-set values of radiant heating power and lighting illuminance influenced participants' preferred settings. Moreover, the adjustable range of light could also affect preferred light settings [86–88]. This suggests that if personal control is available, one could use antecedent conditions and/or the adjustable range of light to 'nudge' employees to choose settings more favorable to their health, performance or building energy saving.

4.5. Limitations

A few limitations in this study are worth noting. Firstly, as suggested in Section 4.1, the current study investigated only the causal route from visual comfort (induced by self-selected light condition) to thermal comfort. Similarly, one could in future work study the opposite direction. Secondly, the reference conditions in this study were not rated with a low visual comfort. In real-life situations where visual comfort is considerably compromised by CCT, the benefits of personal control of CCT may be more pronounced. Also, we only allowed participants to control the CCT at the beginning of Period 2. It is possible that the participants would like to exercise personal control more frequently during Period 2. Therefore, the positive effects of personal control of CCT may be underestimated in this study. In addition, this study was not able to distinguish the effects of merely perceiving control from the effects of personalization (i.e., exercising control) based on the regression models. Last, the test duration in this study was 70 min. The beneficial effects of personal control may accrue over a time span of days. Therefore, it is recommended to investigate the effects of personal control over CCT in the long term.

5. Conclusions

This study investigated two questions: 1) Can increased visual comfort, induced via personal control over CCT, mitigate thermal discomfort in mild cold? 2) Does personal control over CCT benefit cognitive performance and perceived environmental quality (eye-related symptoms, alertness, pleasure and arousal)? The main conclusions are as follows:

- For both antecedent CCTs (2700 K and 5700 K), personal control over CCT largely improved visual comfort, but did not significantly mitigate thermal discomfort.
- Personal control over CCT reduced eye-related symptoms (eye fatigue, eye discomfort and eye strain) after both antecedent CCTs.
- After the antecedent CCT of 5700 K, personal control enhanced planning ability (Hampshire tree task) and verbal ability (grammatical reasoning task), but, unexpectedly, decreased mental spatial manipulation ability (rotation task). Nevertheless, participants perceived less mental demand and higher alertness, along with increased heart rate and reduced heart rate variability. When the antecedent CCT was 2700 K, no significant effects of personal control over CCT were found on cognitive performance.
- Antecedent CCT affected participants' preferred CCT. The low antecedent CCT (2700 K) resulted in a lower preferred CCT than the high antecedent CCT (5700 K).
- The exploratory analysis suggests that, after controlling for the actual CCT, the psychological and personalization effects of personal control of CCT (having control and exercising it to tune settings to one's preference) benefited visual appraisals and mitigated eye-related symptoms, but did not affect thermal appraisals and cognitive performance. In addition, it seemed to reduce mental demand, and boosted perceived performance, pleasure, alertness and physiological arousal.

Together, the results suggest that in office settings with a common CCT ranged from 2700 K to 5700 K, 1) improved visual comfort via personal control cannot causally mitigate thermal discomfort in mildly cold conditions, however 2) Personal control of CCT does mitigate eye-related symptoms, sometimes improves alertness and mental demand, and differentially affects cognitive performance depending on the task type.

CRediT authorship contribution statement

Wei Luo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Rick Kramer:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Maaike Kompier:** Writing – review & editing, Methodology, Conceptualization. **Karin Smolders:** Writing – review & editing, Methodology, Conceptualization. **Yvonne de Kort:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Wouter van Marken Lichtenbelt:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110380.

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