Personal comfort systems and cognitive performance

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Personal comfort systems and cognitive performance: Effects on subjective measures, cognitive performance, and heart rate measures

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ABSTRACT

Personal comfort systems (PCS) that warm or cool local body parts promise individual thermal comfort, energy saving and (metabolic) health in non-neutral thermal environments. However, research on work performance while using a PCS is scarce. We previously tested a PCS that warms the extremities and cools the head and reported that the PCS improved thermal comfort during a ramp of 17-23°C but did not at a stable temperature of 25°C. In the current study, its effects on cognitive performance, subjective measures and task-induced heart rate measures are investigated. Eighteen participants completed two randomized, eight-hour-long dynamic office scenarios: one is *PCS scenario* and another one is *without PCS scenario*. The results show warming the extremities slightly slowed reaction time for a simple task at 19°C ($p < 0.05$) whereas it exerted no effect on complex task performance in 17-21°C. At 25°C however, cooling the head improved complex task performance ($p = 0.053$), which derived from participants' effort increase, whereas it did not affect simple task performance. These findings suggest that the PCS' effects on cognitive performance depended on the task type. Cooling the head, independent from its influence on thermal comfort, plays a significant role in complex cognitive performance in slightly warm conditions.

1. Introduction

Work performance in the office building has an important economic impact on business operation, its value far exceeding that of air-conditioning energy costs [1,2]. To ensure workers' performance and thermal comfort, the ambient temperature is currently controlled in a small range with limited permissible daily and seasonal variations. It is believed that workers' performance might deteriorate outside this stringent temperature range [3]. The relationship between temperature and work performance is often described as an inverted-U shape that stems from a *meta*-analysis study by Seppänen in 2006 [4]. The inverted-U model was adopted in the guidelines byASHRAE [5] and REHVA [6], suggesting that performance peaks at the optimal temperature and that any deviations from the optimal temperature will affect work performance negatively. Instead of ambient temperature, several studies have connected work performance to thermal sensation [7–10]. These studies broadly corroborate the inverted-U shape model with peaking performance near the neutral thermal sensation [7–10]. For example, Geng et. al. [8] measured participants' productivity and thermal sensation in 16-28°C. They found a quadratic relation between thermal sensation votes and relative productivity, where relative productivity was optimal between 'neutral' and 'slightly cool' votes. Furthermore, Lan et al. [11,12] attempted to disentangle the effect of ambient temperature on cognitive performance from the effect of thermal comfort. They revealed that cognitive performance was reduced at elevated air temperature (26-28°C) even when thermal comfort was achieved by adjusting clothing and/or airspeed.

Nowadays, global warming continues and extreme weather conditions occur more frequently [13,14]. Driven by sustainability challenges, researchers have started to rethink the current paradigm of strict temperature control [15–17]. Relaxing temperature ranges offers a significant energy-saving potential [18,19], may elicit some important health benefits [15], and does not necessarily compromise thermal comfort [17,20]. To support the idea of ambient temperature relaxation, the inverted-U shape relationship between temperature and work performance has been reexamined. A competitive alternative is the extended-U shape relationship, derived from Hancock's Maximum Adaptive Model [21]. The maximum adaptive model stresses the human's adaptive ability to maintain performance across a range of temperatures. Unlike the inverted-U shape model proposing a single optimal tempera-

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ture, the extended-U shape relationship describes a broad temperature range, across which the temperature has no discernible effect on cognitive performance. The extended-U model is supported by a multidisciplinary review [22], claiming the evidence suggests that the extended-U shape fits better than the inverted-U shape in moderate indoor thermal conditions. This claim is based on many studies that show no performance differences among different thermal conditions [23–26].

The debate about which model fits better continues to date. Recently, Porras-Salazar et al. [27] reconducted a *meta*-analysis to examine both models and other possible relationships. After including more data from recent literature, no plausible relationship could be established in a moderate temperature range (18-34°C), including inverted-U shape and extended-U shape models. The inconsistency among different (*meta*-analysis) studies and models may be caused by the complexity of influencing factors and their methodological differences [22,27]. The physical environment, the performer and the task are considered to be three main factors affecting cognitive performance [22]. For example, the effects of temperature on cognitive performance have been found to be dependent on task types [28], participants' motivation [9] and intensity of the thermal stress [29].

Although the relationship between cognitive performance and ambient conditions receives much attention, most research still focuses on cognitive performance in a stable and uniform thermal condition. A dynamic and non-uniform condition may support temperature relaxation while fulfilling the need for thermal comfort. For example, studies indicate that a moderately drifting temperature (17-25°C) will not cause a thermally unacceptable condition [20,30]. Moreover, personal comfort systems (PCS) have been shown to provide individual thermal comfort [31], to relax comfortable ambient temperature ranges to 14–32°C [31,32], and to potentially benefit (metabolic) health [33,34,35]. Such PCSs usually create a non-uniform thermal condition by warming up or cooling down participants' local body parts.

To date, however, very little is known about the effect of PCSs on cognitive performance and how it shapes the relation between thermal comfort and cognitive performance. Therefore, the current paper aims to investigate the effect of PCSs on cognitive performance. Recently, the authors have developed a novel PCS that targets only the extremities and the head [35]. The designed PCS was evaluated in a moderately drifting temperature profile (17°C to 25°C with a constant rate of 1.5°C per hour) to explore the limits of comfortable ambient temperature. Although the employed temperature profile was dynamic, the thermal perceptions in such slow temperature drifting would be similar to that in a static scenario [30,36]. The results indicated that the designed PCS improves thermal comfort while preserving the positive health effects from thermal stimulation of the body in cold conditions [35]. From the same experiment, the current paper will investigate the effects of the designed PCS on cognitive performance from different angles: 1) primary cognitive task performance, 2) subjective perception of cognitive load, 3) task-induced physiological responses (including heart rate and heart rate variability), 4) alertness and arousal 5) interaction between tasks and performers (including frustration level, self-perceived performance, effort devoted and motivation). The results will be used to discuss the link between cognitive performance and temperatures/thermal perceptions in a spatially non-uniform environment, where environmental thermal conditions vary among different parts of the body.

2. Method

2.1. Ethical consideration and participants

This study was conducted under the Declaration of Helsinki and was approved by the Medical-ethical committee of Maastricht University. Eighteen participants were measured throughout the winter and fall seasons in the Netherlands (nine males and nine females taking hormonal contraception, all Caucasian, healthy, 18 – 40 years old with a BMI of 18.0 – 27.5 kg/m^2). Results on *thermal perceptions* (e.g. thermal sensation and thermal comfort), *thermoregulation* (e.g. skin temperature) and *perception of the indoor environmental quality* (e.g. perceived air quality) have been previously published [35].

2.2. Experimental setup

This study was carried out in a climate chamber where an office situation was emulated (Metabolic Research Unit of Maastricht University, Maastricht). The chamber's mean radiant temperature was close to the ambient temperature. The environmental airspeed inside the chamber was controlled at 0.2 m/s, and the relative air humidity was between 40 % and 55 % RH. In addition, the lighting conditions remained at 4000 K with 500 lx on the work plane.

To warm the extremities and cool the head, the designed PCS consists of a heating desk, a heating feet mat and two ventilation fans (Fig. 1). The heating desk could heat a U-shaped surface to three levels: 31°C (low), 34°C (medium) and 37°C (high). The temperature of the heating feet mat could be set to 36°C, 41°C or 46°C. The fans could increase the airspeeds around the participants' head area to three levels (about 80 cm away from the fan): 0.3 m/s, 0.6 m/s and 1.2 m/s. The participant could control those three devices individually by pressing three buttons on the desk. Each press would increase the devices' power or turn off the device when it had reached the maximum level. The direction of the two ventilation fans was adjusted to target the participants' head region before the measurement. The settings of each device were recorded to assess participants' usage.

2.3. Experimental protocol

A randomized within-subject design was employed. The participants performed two scenarios on two test days: (i) with full control over the Personal Comfort System (PCS scenario), (ii) without PCS (NOPCS scenario). The two scenarios were tested at least one day apart to avoid possible acute thermal acclimation induced by the experiment's intervention and within two weeks to prevent seasonal effects of changing outdoor conditions [35]. The sequence of the two scenarios was randomly assigned to participants.

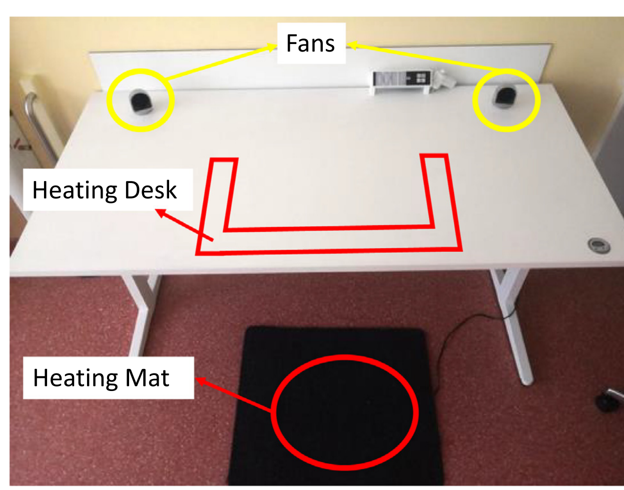


Fig. 1. Designed personal comfort system consisting of two ventilation fans (yellow ovals), a heating desk and a heating mat. The red areas indicate the heating areas (). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) adopted from [35]

A day before every scenario, the participants received a standardization session to familiarize them with the test procedure, climate chamber and the PCS. They were instructed to follow a standardized lifestyle 24 h before the test days. During those 24 h, they were asked to 1) refrain from coffee and alcohol intake, and from moderate to vigorous activity; 2) eat similar diets; 3) avoid food and drinks other than water after 22:00 h; 4) sleep at a regular bedtime for a reasonable amount of sleep. In addition, the participants practiced the cognitive tasks for 1.5 h to reduce the learning effects during the experiment. The participants were encouraged to try their best at the cognitive tasks on the following test day.

Upon arrival on the test day, the participant stayed at a neutral temperature (23°C) to stabilize their thermal state. Meanwhile, wearable sensors were attached to measure skin temperature, hand skin blood flow, heart rate, blood pressure and physical activity. Participants wore standardized clothing (0.8 Clo) and laid on the bed for 30 min to evaluate their basal metabolic rate. Afterwards, the participants were transferred to the climate chamber for 8 h. We used a drifting temperature profile to reach a non-neutral thermal condition in the climate chamber. A moderately drifting temperature (17-25°C) has been tested in our research group [20,30,35]. The findings showed that it stimulated humans' thermoregulation and did not cause a thermally unacceptable condition [20,30,35]. Moreover, a dynamic temperature might also reduce building energy consumption [37]. Therefore, a similar drifting temperature profile was applied to the climate chamber: the indoor temperature started at 17°C and increased to 25°C at a constant rate of change of 1.5°C/h, see Fig. 2. The starting temperature of 17°C was chosen to avoid shivering [30] (the predicted mean vote is around −1.5). Based on ASHRAE standard 55 [38] and ISO standard 7730 [39], the maximum temperature of 25°C falls into the thermal comfort zone (the predicted mean vote is around + 0.5). The imposed ramp fits the maximal permissible rate of change according to ISO 7730 [39], i.e. 2°C/h, under which the thermal sensation is considered not being affected by the previous thermal experience [30,36]. The ambient temperature first started at 17°C for 30 min to let participants acclimate to the cold temperature. Subsequently, the ambient temperature increased at a rate of 1.5°C/h. Once the temperature reached 25°C, it was maintained at 25°C for 130 min. At the same time, the participants were able to control the device freely in the PCS scenario. The measured ambient temperature in both scenarios can be found in our previous paper [35].

The primary cognitive task performance, subjective perception of cognitive load, alertness, arousal and interactions between tasks and between performers were assessed at 17°C (t = 30 min), 19°C (t = 110 min), 21°C (t = 190 min), 23°C (t = 270 min) and 25°C (t = 350 min, 415 min and 480 min). No monetary incentive or any encouragement was given during the measurements, so participants were self-motivated rather than motivated by the researchers when they performed the tasks. The task-induced physiological responses (heart rate and heart rate variability) were monitored continuously. In addition, participants did 5-min stepping exercises twice to mimic normal office walking activity and also rested in a supine position twice to measure resting metabolic rate. To avoid mental fatigue, the participants rested about 40 to 60 min in between the two assessments of the cognitive tasks, where they were allowed to do office related activities or relax. In addition, breakfast and lunch were standardized and provided by the researcher at fixed times. Fig. 2 shows the details of the experimental protocol.

2.4. Measurements

2.4.1. Thermal perceptions and skin temperatures

Whole-body thermal sensation and comfort were measured using visual analogue scales according to ISO standard 10551 [40] (Fig. S1A, B). In addition, the local thermal sensations of nine body parts were assessed by the same thermal sensation scale (head, neck, torso, upper arm, lower arm, hand, thigh, calf and feet, Fig. S1A). Based on ISO 9886 [41], fourteen temperature sensors (iButtons DS- 1922 L, Maxim Integrated) were placed on the body to measure the mean skin temperature, including forehead, neck, torso (four sites), upper arm, forearm, hands, upper legs (two sites), lower legs (two sites) and feet. The thermal perceptions and skin temperature data have been reported in our previous paper [35].

2.4.2. Primary task performance

Broad literature demonstrates that the effect of thermal environments on cognitive performance is highly dependent on task type and task complexity [22]. Therefore, a simple task (Anticue

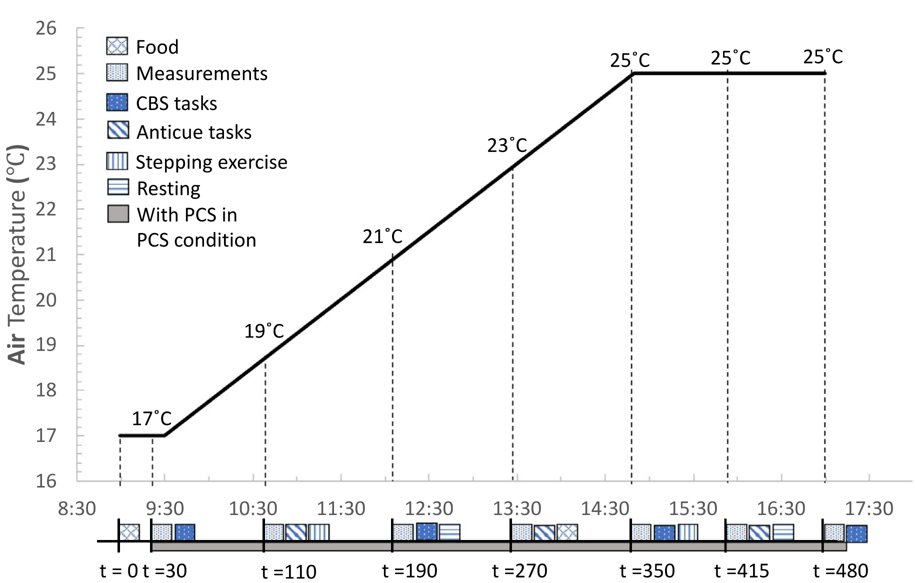


Fig. 2. experimental protocol.

task) and a complex task (Cambridge Brain Sciences (CBS) task) were selected. Those two tasks were performed alternatingly, see Fig. 2. The CBS tasks were performed at 17°C (t = 30 min), 21°C (t = 190 min), and 25°C (t = 350 min and 480 min). The Anticue task was performed at 19°C (t = 110 min), 23°C (t = 270 min) and 25°C (t = 415 min).

2.4.2.1. Anticue task. The Anticue task is a multiple-choice reaction time (RT) task, developed by Adam et al. [42]. It has two types of cues randomly mixed: "neutral"-cue (100 trials) and "anti"-cue (100 trials). The performance on the two cue types reflects different cognitive control processes: "anti"-cue measures proactive inhibitory control while "neutral"-cue assesses simple reactive cognitive control [42]. Proactive inhibitory control is relevant in many different real-life domains, including food intake, sporting, gambling, and decision making. The sensitivity of the task in assessing inhibitory control has been confirmed in several studies [42,43].

The Anticue task asks participants to react to a stimulus in one of the four boxes presented on the screen by pressing the corresponding keys using both hands' index and middle finger (Fig. 3). During the task, a row of four empty boxes is continuously visible on the computer monitor. At the start of each trial, a visual warning signal (a small red square) appears between the two inner boxes, flickering three times in a time window of 750 ms and then disappears. After an additional 750 ms, the cue signal starts. In *"anti"-cue trials*, the two leftmost or two rightmost boxes turn red, whereas, in *"neutral"-cue trials*, all the four boxes turn red. A green target is then presented after a cue-target interval of 100, 150, 250, 450, or 850 ms. For *"neutral"-cue trials*, 1 of the 4 boxes turns green. For *"anti"-cue trials*, 1 of the 2 empty boxes turns green. Participants are instructed to react to the green target as quickly as possible by pressing one of the four response keys located on the bottom row of the keyboard ('Z', 'X', '.', '/'), after which all boxes turn empty again. When an incorrect response is made, an error message is shown briefly. The intertrial interval is 1.5 s.

In *"anti"-cue trials*, the cognitive mapping between cue location (left, right) and response hand (right, left) is mirror-symmetrical and thus incongruent. That is, an anti-cue appearing on the left side of space calls for a keypress response with 1 of the 2 fingers of the right hand, and vice versa. Hence, anti-cue performance requires a top-down, intention-driven process that selectively inhibits fingers on the ipsilateral hand and primes fingers on the contralateral hand before the target appears. In *"neutral"-cue trials*, the spatial cue occupies all four possible target locations, thereby negating the possibility to implement a selective motor set. Hence, the neutral-cue is a simple four-choice RT task indexing reactive cognitive control.

2.4.2.2. Complex tasks. The complex tasks are parts of a commercial online test battery (*https://www.cambridgebrainsciences.com*), of which the sub-tasks assess a variety of different cognitive processes based on classical psychological paradigms [44]. With neuroimage and simulation technology, the CBS test battery has been shown to co-recruit three anatomically distinct brain networks, and the sub-tasks load differently on those three networks [44]. Four different sub-tasks were chosen to assess the cognitive skills involved in the office activities including planning, verbal ability, working memory and mental spatial manipulation.

For *planning*, the Hampshire tree task was used to test the ability to act with forethought and sequence behavior in an orderly fashion to reach specific goals (Fig. 4A). Initially, nine numbered balls are slotted randomly onto the branches of a tree-shaped frame. The participant has three minutes to rearrange them into numerical order in as few moves as possible. Puzzles become more difficult as the participants succeeds.

For *verbal ability*, the grammatical reasoning task requires participants to indicate if a statement describes the relationship of geometrical graphs (Fig. 4B). Participants have 1.5 min to answer the questions. A high score requires responding quickly and accurately.

For *working memory*, a forward digital span task was used to test verbal working memory through remembering a sequence of numbers (Fig. 4C). The difficulty of this task changes dynamically. The number of digitals increases after a correct answer and decreases after a wrong answer. Once the participants answer wrong three times in a row, the task is ended and the performance is indicated by the average number of digitals correctly remembered.

For *mental spatial manipulation*, a spatial rotation task was used to assess the ability to efficiently manipulate mental representations of objects (Fig. 4D). Participants have 1.5 min to judge if two grids of colored squares are the same by rotating one grid a multitude of 90°. The difficulty is adjusted depending on whether the previous answer was correct. The adjustable difficulty of the tasks aims to prevent possible ceiling and floor effects. According to Hampshire's findings [44], these four sub-tasks have good test–retest reliabilities. A comprehensive CBS task score is derived by adding the standardized scores of the four tasks.

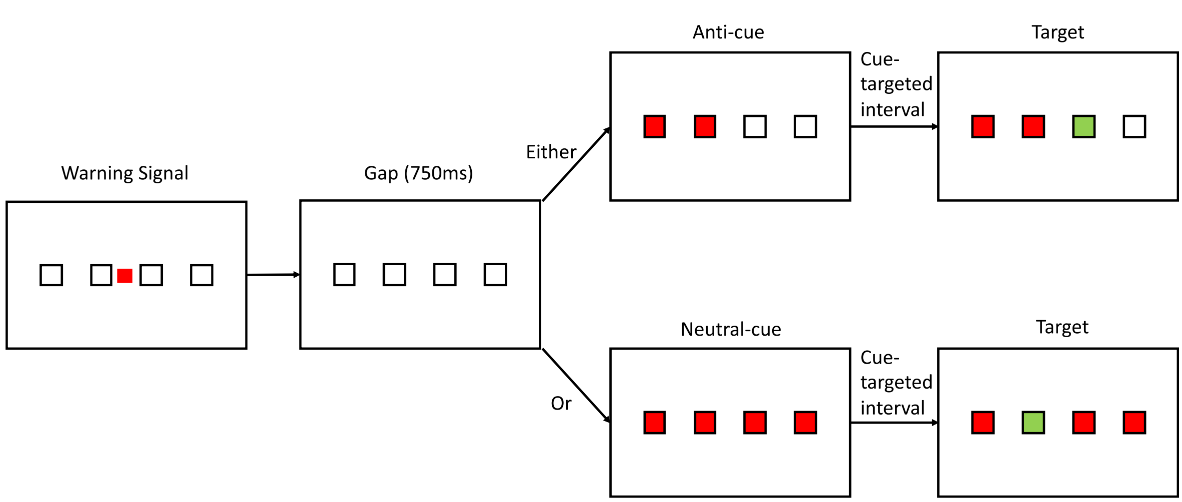


Fig. 3. Schematic flowchart of the anti-cue and neutral-cue trials.

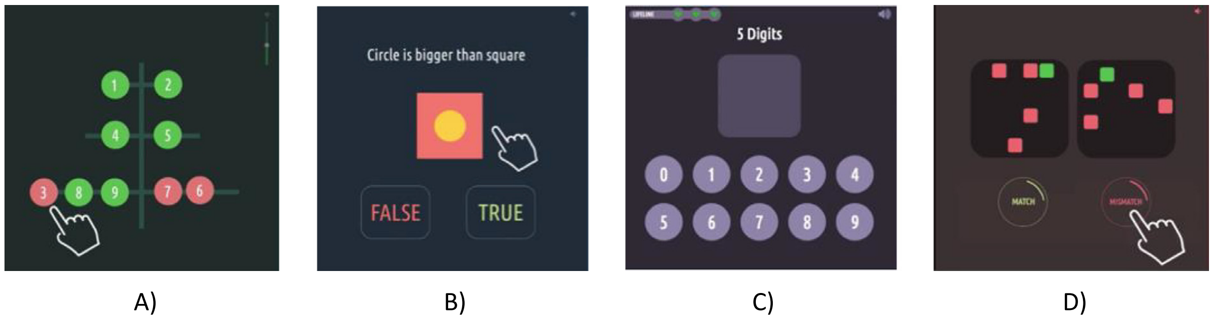


Fig. 4. Cambridge brain sciences tasks: A) Hampshire tree task, B) grammatical reasoning task, C) forward digital span task, D) spatial rotation task. (the pictures are from the website, www.cambridgebrainsciences.com).

2.4.3. Subjective perception of cognitive load

The NASA task load index (NASA-TLX) was used for the self-estimated evaluation of workload with multidimensional measurements [45]. It includes six visual analogue scales (Fig. S1C), ranging from 0 (low) to 100 (high). Three scales (physical demand, mental demand, temporal demand) aim to measure the demands imposed on the participant. Thus, these three scales were selected to evaluate participants' cognitive load.

2.4.4. Task-induced physiological responses

Previous studies have demonstrated that heart rate and heart rate variability (HRV) are associated with workload [46]. Therefore, heart rate and HRV were measured using a chest belt (*H*10, polar, USA, RR interval accuracy is 99.6 % [47]). The RR interval data of the chest belt was obtained for the analysis. The RR interval is the time interval between two successive R-waves on the electrocardiogram. HRV was metered by pNN50, the proportion of the number of successive heartbeat intervals exceeding 50 ms divided by the total number of RR intervals. In addition, the body temperature (thermal comfort) may also affect the heart rate and heart rate variability [48,35]. In order to separate the effect of task performance from the effect of body temperature, the task-induced heart rate and task-induced HRV were calculated as the values during performing the cognitive tasks minus the values during the 10-minutes resting before the task.

2.4.5. Arousal and alertness

The self-assessment manikin scale was used to gauge participants' arousal [49] (Fig. S1D). Alertness was assessed by the Karolinska sleepiness scale on a 9-point Likert scale [50] (Fig. S1E).

2.4.6. Interaction between tasks and performers

Another three scales of NASA-TLX were used to measure the interaction between the participant and the task (perceived performance, effort investments, and frustration level) [45] (Fig. S1C). In addition, the motivation was evaluated by a visual analogue scale adopted from Cui et al. [9] (Fig. S1F).

2.5. Data analysis

For the Anticue task, the RT data below 150 ms or above 1000 ms were treated as outliers and excluded from the analysis [42]. For the CBS task, extreme outlier scores (>4*SD of population mean) were excluded as well [44]. To assess the workload difference between the two tasks, the averaged data of the CBS task at 21 °C and 25 °C (t = 190 and 350 min, NOPCS scenario) were compared to the data of the Anticue task at 23 °C (t = 270 min, NOPCS scenario). The significance was determined by a paired *t*-test.

The differences between the two scenarios were tested using a mixed linear effects model (R package LmerTest [51] and Emmeans [52]). The participants were included as a random factor, and the scenarios, measurement timepoints and their interactions were added as fixed factor. Considering that the actual ambient temperature differed from the protocol, the difference between the actual ambient temperature and the protocol temperature was also treated as a fixed factor. Covariates were added to improve the power of the mixed linear effects model, including body surface area to mass ratio, fat-free mass to body surface ratio, gender and age [35]. The sequence of the scenario was also considered as a covariate to account for the possible learning effect. A 'top-down' modelling strategy was employed and only significant covariates were kept in the model [53]. The assumptions of the mixed linear effects model were checked. In the case of the rotation task, the score was logarithmically transformed to stabilize the variance.

To investigate the possible mechanisms regarding how the PCS affected cognitive performance, a mediation analysis was performed under the mixed linear effects model framework using R package Mediation [54]. The mediation effect was tested using a built-in bootstrapping method. Ten thousand simulations were run to obtain the estimations of p-values.

The statistical analyses were performed using an open-source software package in R Studio 1.3.1073. An α of 0.05 was used as the cut-off value for significance (all * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, unless stated otherwise). For the box plots, the medians, the means and the outliers are represented by horizontal lines within the boxes, dots in the boxes and crosses outside of the boxes, respectively.

3. Results

3.1. Participants' PCS-usage

As expected, most participants warmed their extremities using the heating device in cold conditions (17-21 °C, Fig. 5). When the ambient temperature reached 23 °C, the use of the heating device decreased and the use of the cooling device increased. At 25 °C, the fan became the dominant device in use to cool participants' head region.

3.2. Primary cognitive task performance

3.2.1. Distinct differences between two tasks

The CBS task was more mentally and temporally demanding than the Anticue task according to the NASA-TLX questionnaire ($p < 0.05$, Table 1). In line with this, the CBS task required more effort ($p < 0.05$, Table 1). However, no significant difference in physical demand was found between the two task types. The sequence of scenarios significantly affected the CBS task performance, but not the Anticue task performance (Table 2). In addition, the CBS task performance correlated with motivation and effort. In

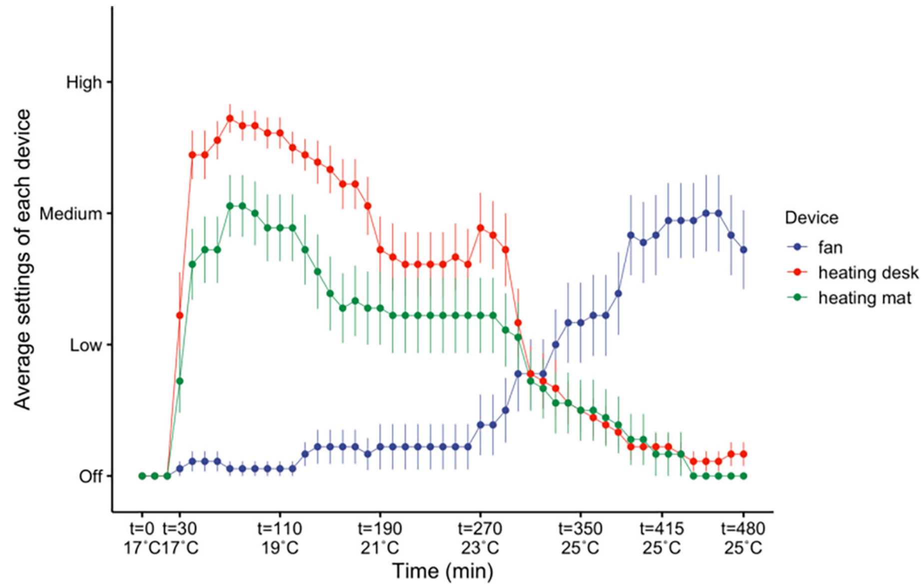


Fig. 5. Average settings of each device during PCS scenario. The data are shown as means ± 1 standard error.

contrast, the Anticue task performance correlated with alertness ($p < 0.05$, Table 2). Both tasks did not linearly associate with arousal level (Table 2).

3.2.2. Simple task - Anticue task

In the NOPCS scenario, the effect of timepoint on RT was not significant for the neutral-cue trials, anti-cue trials or the average of the two cue types (Fig. 6A, C, E). Neutral-cue performance reflects reactive cognitive control. Compared to the NOPCS scenario, the PCS significantly slowed neutral-cue RT in cold conditions (19℃, 10.7 ms slower, $p < 0.01$, $d = 0.44$, Fig. 6A). No significant difference emerged in thermally neutral conditions (23℃, $p = 0.085$, $d = 0.27$) or in slightly warm conditions 25℃ (Fig. 6A). The neutral-cue error rates were similar between the two scenarios across all temperatures (Fig. 6B).

Performance on anti-cue trials, requiring proactive cognitive control, was not significantly affected by the PCS, for RT nor for error rates (Fig. 6C, D). Overall, the PCS significantly increased the average RT for two cue types at cold conditions (19℃, 7.6 ms, $p < 0.05$, $d = 0.24$, Fig. 6E), whereas average error rates were equal for both scenarios across all temperatures (Fig. 6F).

3.2.3. Complex task – CBS task batches

Performance on the CBS task remained relatively stable over time in the NOPCS scenario (Fig. 7). The PCS did not generally influence cognitive performance on the complex task in cold conditions (17℃ and 21℃, Fig. 7), however, in slightly warm conditions (25℃, t = 350 min), the digital span task score, rotation task score and comprehensive CBS score were improved by the use of PCS ($p < 0.05$, Fig. 7C, D, E). Notably though, at the end of the eight-hour measurements (25℃, t = 480 min), performance on all four CBS tasks was again similar between the two scenarios (Fig. 7). On average, the PCS significantly improved the rotation task score ($p < 0.05$, Fig. 7D) and the comprehensive CBS task score ($p = 0.053$, Fig. 7E) in slightly warm conditions.

3.3. Subjective perception of workload

The perceived mental demand and temporal demand towards the tasks showed no clear relation with the temperature (Fig. 8A, C). Furthermore, the PCS did not show a clear impact on the mental demand and temporal demand (Fig. 8A, C). On the other hand, for the CBS task, the perceived physical demand differed over timepoints ($p < 0.05$, left parts of Fig. 8B). The perceived physical demand was lowest at 17℃. Compared to the NOPCS scenario, the PCS significantly decreased the physical demand at 25℃, regardless of task type ($p < 0.05$, Fig. 8B).

3.4. Task-induced physiological responses

No significant effect of the PCS on task-induced heart rate and task-induced heart rate variability were found (Fig. 9).

3.5. Arousal and alertness

In reference [35] we already reported that the overall arousal – across all temperatures and tasks – was higher in the PCS conditions. Here we report these data again, but separated per temperature condition and task. In the NOPCS scenario, the average arousal decreased over time and suddenly increased at the end of the eight-hour measurements (Fig. 10A, the effect of timepoints: $p < 0.001$). Likewise, there was a slight rise in sleepiness over time in the NOPCS scenario and a drop at the end, t = 480 min (Fig. 10B, the effect of timepoint: $p = 0.051$). After excluding the sudden-

Table 1
Distinct differences between two tasks based on the NASA-TLX questionnaire (mean ± standard deviation).

	CBS task	Anticue task	Difference	Significance
Mental demand	63.2 ± 17.2	37.7 ± 24.8	25.5	$p < 0.001$
Physical demand	31.7 ± 27.1	31.8 ± 26.4	−0.11	$p > 0.10$
Temporal demand	59.2 ± 19.5	43.9 ± 29.1	15.3	$p < 0.05$
Effort	58.3 ± 16.9	45.8 ± 23.1	12.5	$p < 0.05$

Table 2
Correlations between variables and task performance.

	Standardized regression coefficients	Comprehensive task score (CBS task)	Standardized regression coefficients	Average RT for two cues (Anticue task)
Scenario Sequence	0.379	$p < 0.001$	0.002	$p > 0.05$
Motivation	0.283	$p < 0.001$	−0.003	$p > 0.05$
Alert	<0.001	$p > 0.05$	0.162	$p < 0.001$
Arousal	−0.033	$p > 0.05$	0.011	$p > 0.05$
Effort	0.261	$p < 0.01$	0.040	$p > 0.05$

change data at the end in the NOPCS (t = 480 min), the arousal and sleepiness present a linear correlation with the ambient temperature in the NOPCS scenario ($p < 0.05$, Fig. 10C, D). For the PCS scenario, arousal and sleepiness remained steady (Fig. 10A and B, all the effects of timepoint: $p > 0.05$).

Compared to the NOPCS scenario, participants felt more aroused using the PCS at most of the timepoints (Fig. 10A). For the CBS task, the PCS induced more arousal in both cold and warm conditions. For the Anticue task, a significant increase in arousal was only found in warm conditions ($p < 0.01$, 25℃, t = 415 min). In addition, people felt less sleepy (more alert) at 25℃ (t = 350 min) when they performed the CBS task using the PCS. No significant differences in alertness between the two scenarios were found at other timepoints.

3.6. Interactions between tasks and performers

In line with the increase of the average RT at 19℃, participants' frustration level was higher when they performed the Anticue task at 19℃ in the PCS scenario ($p < 0.05$, right part of Fig. 11A). At other timepoints, frustration level was unaffected by the scenario.

Perceived performance was higher with a PCS than without it for all the timepoints. In cold conditions (17℃ and 21℃), the PCS improved the perceived performance on the CBS task ($p < 0.05$, left part of Fig. 11B). However, in warm conditions (25℃), no difference was found (left part of Fig. 11B). For the Anticue task, the perceived performance was similar between the two scenarios (left part of Fig. 11B). The by-scenario average data indicated that PCS generally boosted perceived performance ($p < 0.05$, right part of Fig. 11B).

Consistent with the performance improvement on the CBS task at 25℃ (t = 350 min, Fig. 7E), participants trended towards being more motivated (non-significant, $p = 0.079$, Fig. 11C) and recruited more effort ($p < 0.05$, Fig. 11C) in the PCS scenario at 25℃ (t = 350 min). These differences again disappeared at the end of the 25℃ (t = 480 min, Fig. 11C, D). Overall, the PCS made participants put more effort into the CBS task in slightly warm conditions ($p < 0.05$, 25℃, Fig. 11C).

3.7. Mediation analyses

Previously, we reported the effects of a PCS on thermal perceptions, thermoregulation and perceptions of indoor environmental quality [35]. It was shown that the PCS successfully altered the skin temperature/thermal sensation of the extremities and the head. However, the whole-body thermal perception was improved by the PCS only during 17 – 23℃ drift, i.e. not during the stable 25℃ in the afternoon. On the other hand, at 25℃, the perceived air quality and air freshness were improved and eye strain was mitigated. In addition, the PCS boosted arousal and pleasure over the full 17-25℃ range [35]. In the current paper, analyses suggested that the PCS increased the average RTs at 19℃, whereas the PCS improved the CBS task performance at 25℃, along with changes in motivation, effort, arousal and alertness. To explore potential mechanisms behind these effects, all relevant changes were tested using mediation analyses (Table 3).

The results of our mediation analyses show that the effect of our PCS on the average RT was partially mediated via hand thermal sensation (Table 3). Remarkably, the analyses suggest that by elevating hand thermal sensation, the PCS decreased the average RT, i.e. increased response speed ($p < 0.05$, Fig. 12A). However, beside the indirect path (the mediation effect) via hand thermal sensation, the PCS also directly increased the average RT, i.e. slowing responses ($p < 0.05$, Fig. 12A), in total, resulting in a higher RT with PCS than without in 19℃.

A similar analysis in warm, 25℃ condition suggests that effort significantly and fully mediated the relationship between the PCS and the CBS task performance at 25℃ ($p < 0.01$, Table 3). PCS improved CBS task performance by increasing the effort participants put into the task ($p < 0.05$, Fig. 12B). After adding effort as a mediator, the remaining direct effect of PCS on CBS task performance became insignificant (Fig. 12B). To further explore how the PCS influenced effort, a similar mediation analysis treating effort as a dependent variable was conducted. It showed a trend for head skin temperature mediating the positive effect of cooling on effort, but the indirect path (the mediation effects) did not reach significance ($p = 0.09$, Fig. 12C).

4. Discussion

We investigated the effects of a PCS that targets the extremities and the head on cognitive performance in moderate ambient thermal conditions comprising a ramp from 17℃ to 25℃. An eight-hour long office scenario was emulated, where the participants were self-motivated in performing cognitive tasks. We found that the effects of PCS on cognitive performance depended on task type. In cold conditions, the PCS (warming the extremities) increased the average RT for two cues in the simple Anticue task at 19℃ whereas it exerted no effect on performance in the complex CBS task in 17-21℃. In contrast, for slightly warm conditions (25℃), the PCS (cooling the head) had no impact on the performance of the Anticue task but it did improve performance on the comprehensive CBS task score. Mediation analyses unraveled that the PCS partially accelerated the response speed on the Anticue task by elevating the hand thermal sensation at 19℃, despite the fact that the total effect of the PCS slowed response speed at 19℃. On the other hand, the improvement of the comprehensive CBS task score at 25℃ was fully mediated by an increase of effort investment using the PCS at 25℃.

4.1. Warming extremities in mild cold does not affect complex cognitive performance

Surprisingly, the PCS slowed the response speed in the Anticue task at 19℃ with error rates similar to that in the NOPCS scenario (Fig. 6) while we previously reported that thermal comfort was improved by the PCS at 19℃ [35]. The reason why the PCS increased the reaction time at 19℃ is still inconclusive. We initially expected that warming the extremities would improve manual dexterity,

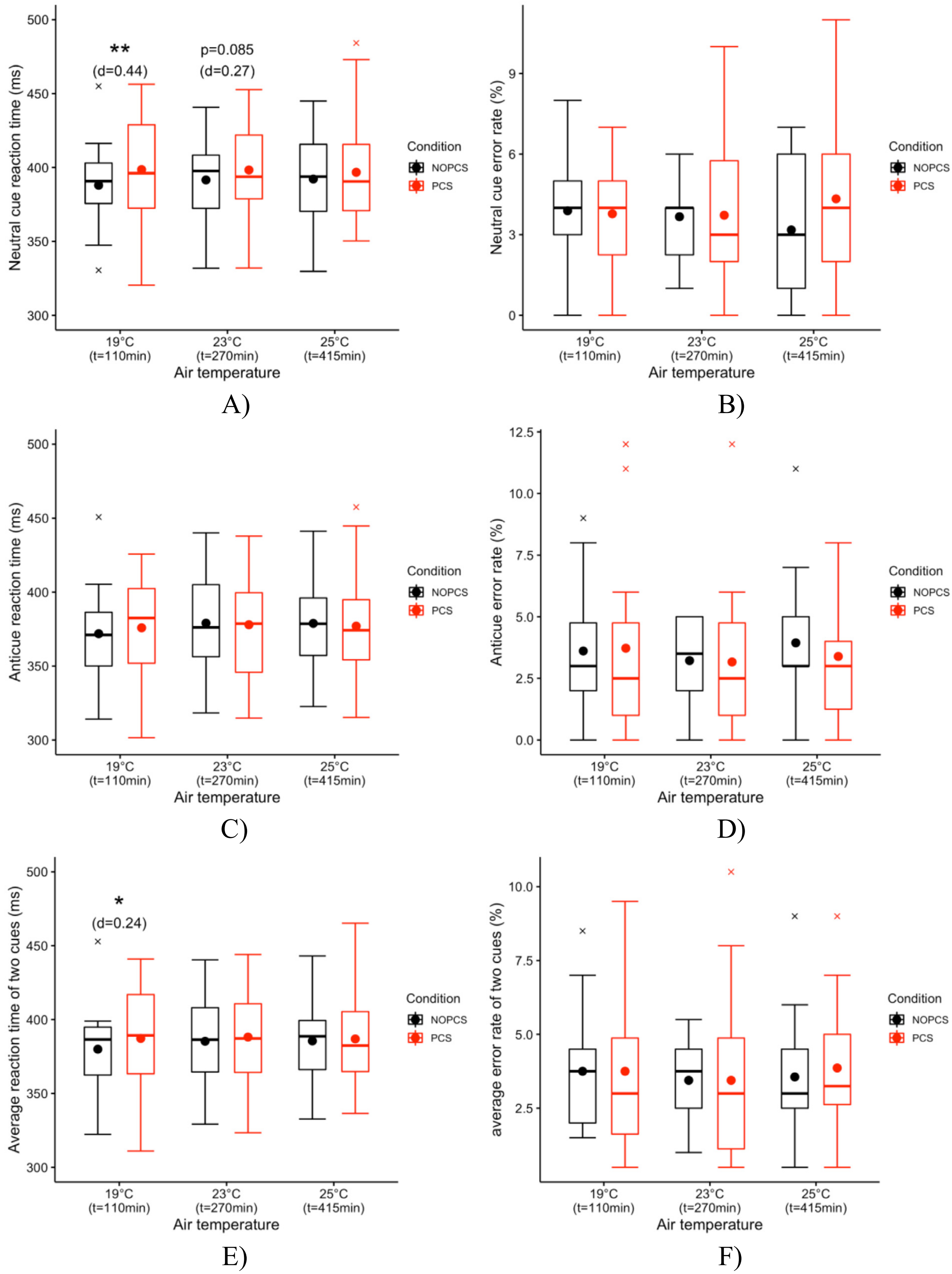


Fig. 6. Anticue task performances: A) Neutral cue reaction time, B) Neutral cue error rate, C) Anticue reaction time, D) Anticue error rate, E) Average reaction time for both cues, F) Average error rate for both cues. The symbol * indicates p < 0.05, ** indicates p < 0.01, x indicates potential outliers.

therefore, increase response speed. The mediation analysis partially corroborates our expectations. Indeed, the PCS decreased the reaction time via elevating the hand thermal sensation (Fig. 12). However, due to other, as of yet unknown paths, the PCS slowed the reaction responses in total. A potential explanation would be that the PCS improved thermal comfort at 19C, and that

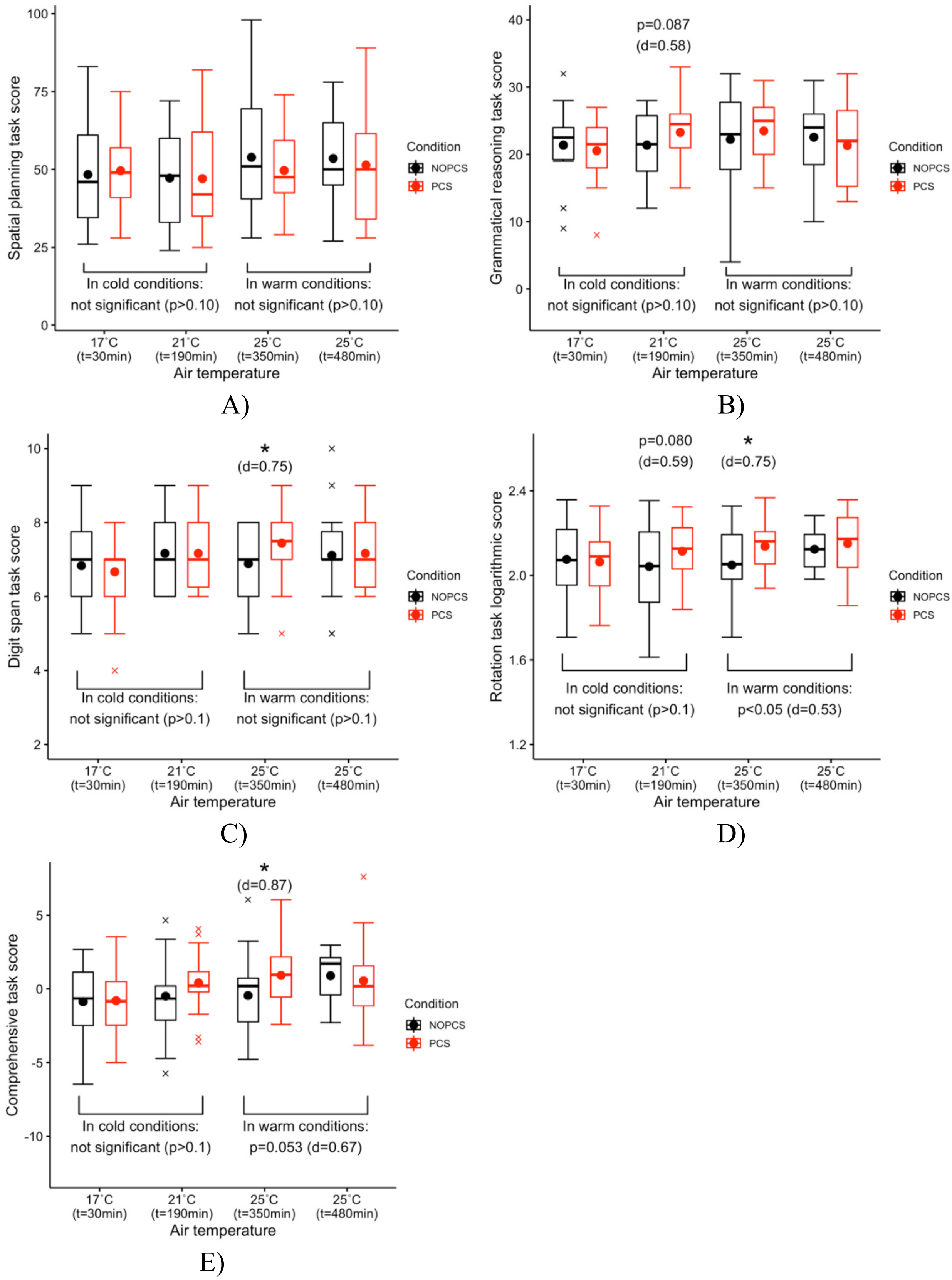
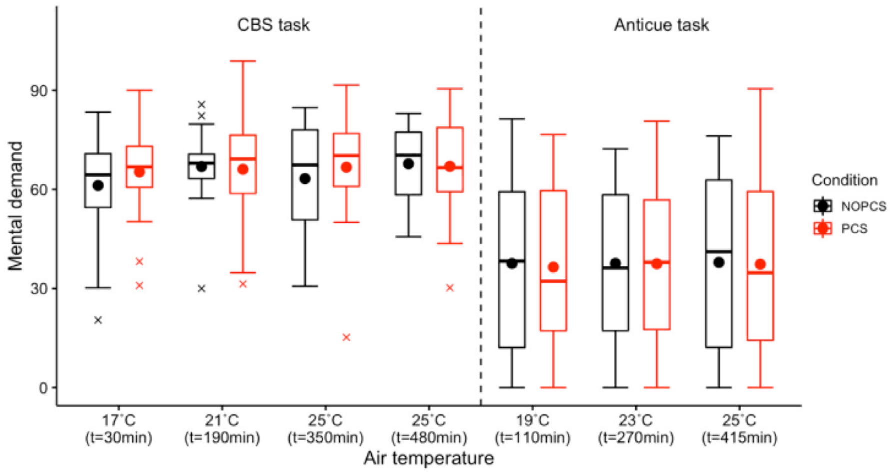
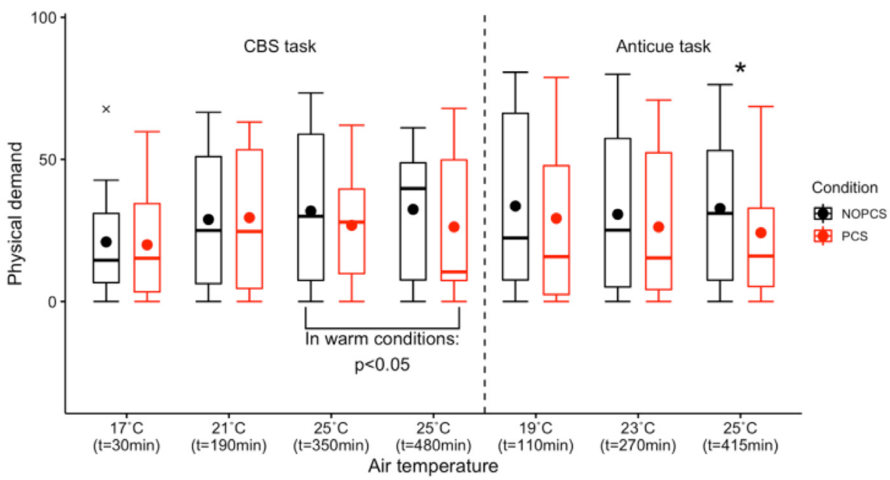


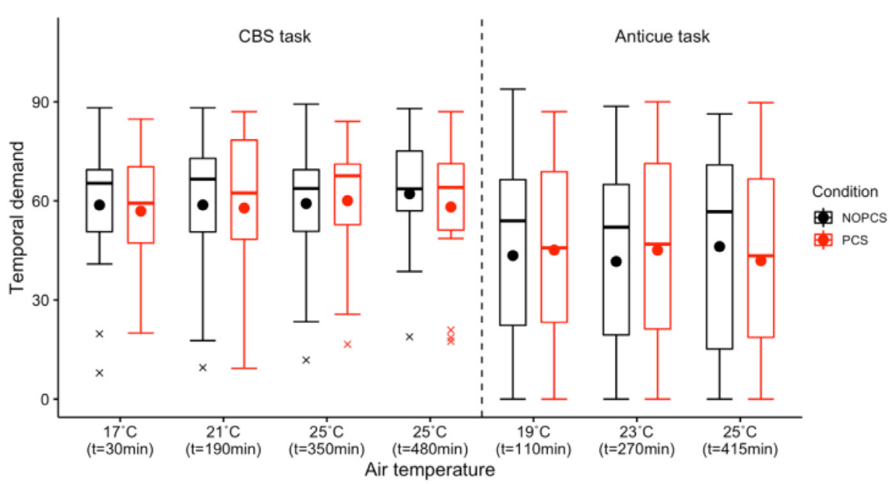
Fig. 7. CBS task performances: A) Spatial planning task score, B) Grammatical reasoning task score, C) Digital span task score, D) Rotation task logarithmic score, E) Comprehensive CBS task score, summarizing four complex tasks into one general score. The symbol * indicates p < 0.05, x indicates potential outliers.



A)



B)



C)

Fig. 8. Subjective perception of work load: A) Mental demand, B) Physical demand, C) Temporal demand. The symbol * indicates $p < 0.05$, x indicates potential outliers.

this made participants feel more relaxed and less aroused. Low arousal reduces performance at a vigilance task [55]. However, our results refute this explanation as the arousal and alertness were similar at 19℃ between the two scenarios (Fig. 10). In line with this, no significant mediation effects of arousal and alertness were found at 19℃ (Table 3). Moreover, it is also unlikely that the PCS distracted participants. The performance decline only appeared for the simple neutral-cue whereas the performance on

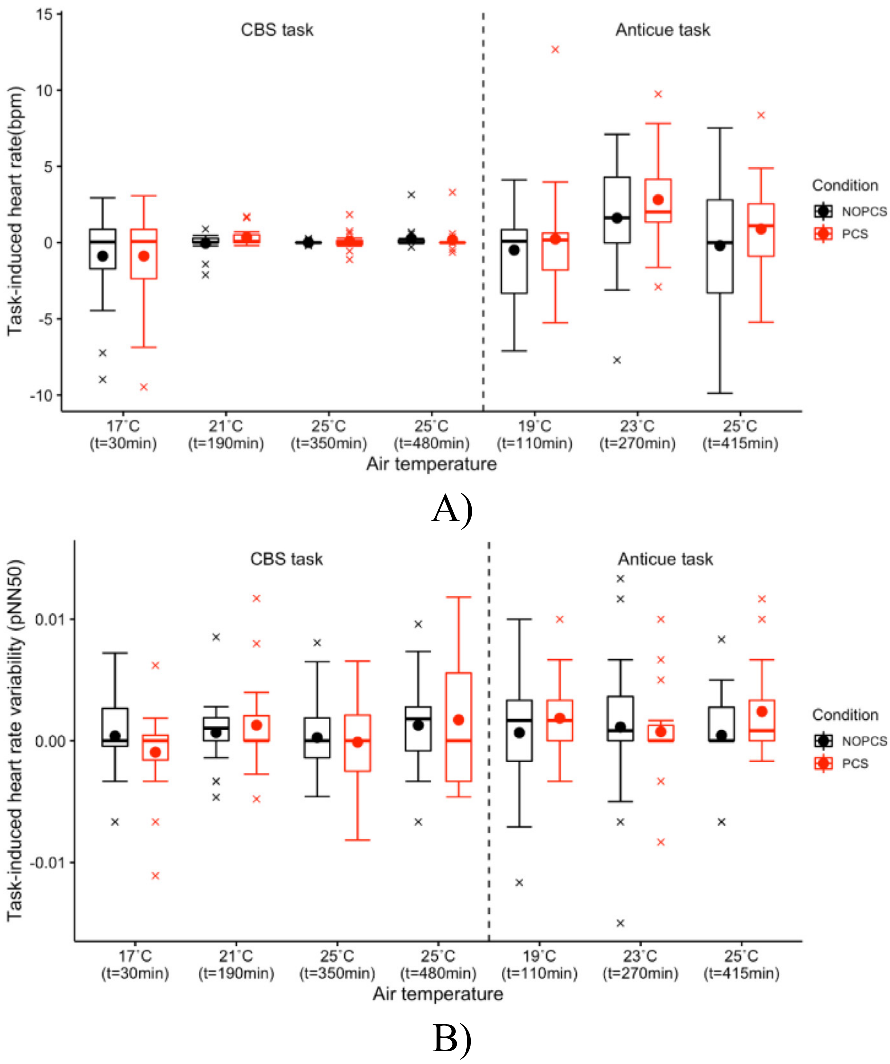


Fig. 9. Task-induced physiological responses: a) Task-induced heart rate b) Task-induced heart rate variability (pNN50 index). The symbol × indicates potential outliers.

the anti-cue was similar between the two scenarios (Fig. 6). A recent fMRI study has shown that anti-cue trials demand much more attentional and monitoring processes than neutral-cue trials [56]. The anti-cue trials and neutral-cue trials were always randomly intermixed in the Anticue task. Therefore, if the PCS caused distraction (e.g. by noise), we would have observed that the distraction led to similar, or, according to the Yerkes-Dodson law [57] even stronger, negative effects on the more complex anti-cue and CBS tasks, which were not affected by the PCS in cold conditions. (Fig. 6C, Fig. 7E).

On the other hand, the PCS merely increased the reaction time of simple neutral-cue by 10.7 ms, which might not be practically meaningful. There was no significant difference for anti-cue responses (Fig. 6C). The neutral-cue stimuli call for reactive cognitive control whereas the anti-cue requires proactive control that is a more top-down, intention-driven process [42]. Thus, it suggests that the top-down, intention-driven process was unaffected by warming the extremities. Moreover, the CBS task assesses a variety of complex cognitive abilities. Likewise, those complex cognitive abilities were also not affected by the PCS in cold conditions (Fig. 7). Taken together, warming extremities in mild cold conditions increased the simple reaction time (in the neutral-cue condition) but it did not affect more complex cognitive performance.

4.2. The head is an important body part for complex cognitive performance in slightly warm conditions

Previous studies indicated that head cooling (breathing zone cooling) sometimes benefits cognitive performance in 28-32°C, along with improvements in thermal comfort [58,59,33,60]. The current study showed that head cooling increased the performance on the complex task already at 25°C (Fig. 7E), and even without improving thermal comfort [35]. This finding suggests that the thermal state of the head, independent from its impact on whole-body thermal comfort, potentially plays an important role in cognitive performance. This would also be in line with another study that reported that warming the head lowered the cognitive performance in a cold environment although the thermal comfort was improved [61].

The disconnection between whole-body thermal comfort and cognitive performance is observed in Lan's studies as well. They found an elevated ambient temperature (26-28°C) reduced cognitive performance even when thermal comfort was achieved by adjusting clothing and/or air speed [11,12]. In Lan's studies, a higher heart rate, lower heart rate variability and a lower oxygen saturation were concurrent with this decrease in the cognitive performance. Therefore, they inferred that those physiological

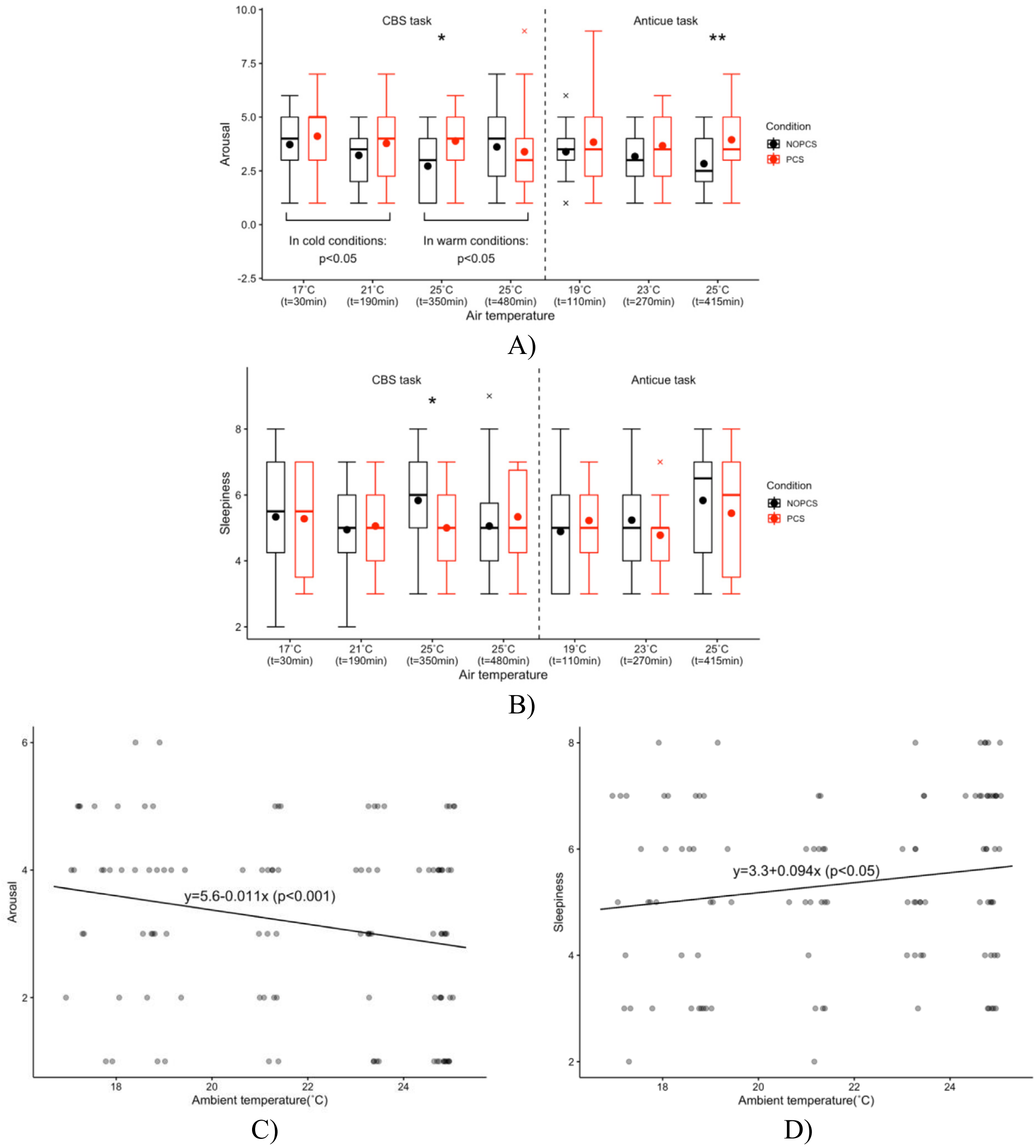
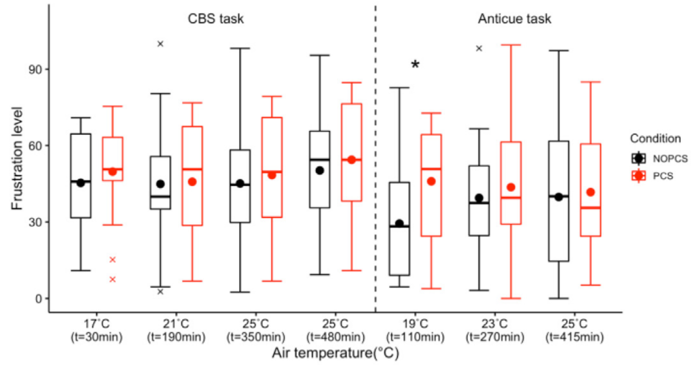


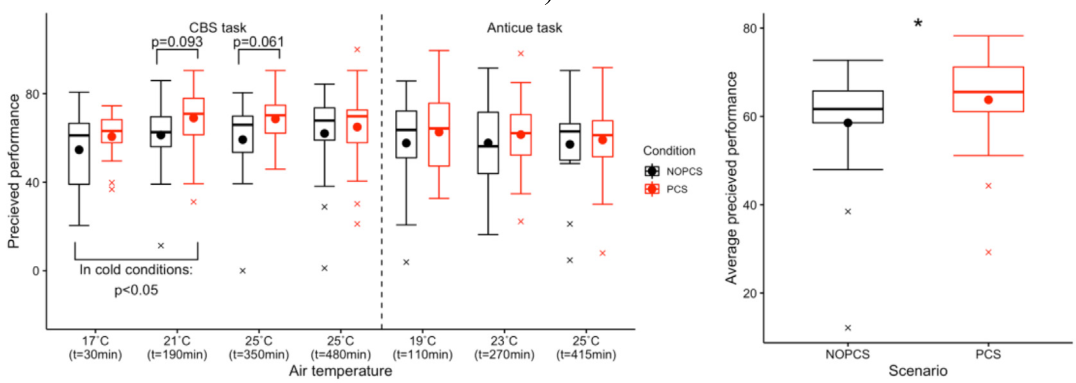
Fig. 10. Arousal and alertness: A) Arousal rating, B) Sleepiness rating, C) Correlation between arousal and ambient temperature in the NOPCS scenario excluding the data at t = 480 min, D) Correlation between alertness and ambient temperature in the NOPCS scenario excluding the data at t = 480 min. The symbol * indicates p < 0.05, ** indicates p < 0.01, x indicates potential outliers.

changes may have caused the reduction in cognitive performance and that a moderately elevated ambient temperature should be avoided for cognitive performance [11,12]. In contrast, in the current study, the PCS increased the heart rate at 25C (see [35]) together with an enhanced CBS task performance using the PCS at 25C (Fig. 7E). This suggests that the slight changes in physiological response that are necessary for thermoregulation do not causally influence complex cognitive performance. Notably, both task and temperature influence heart rate and heart rate variability [48,35]. In the current study, we specifically calculated the task-induced physiological responses and distinguished them from the thermoregulation-induced physiological responses. The results showed that there were no significant differences in task-induced heart rate and heart rate variability between the two scenarios (Fig. 9). Interestingly, in Lan's studies, the forehead temperature was still significantly warmer in the elevated temperature scenarios than the reference scenario [11,12], although the participants were able to adjust clothing and/or air speed to ensure comfort. Therefore, the decrease in cognitive performance in Lan's study may be caused by the 'warm head'. We suggest that future investigation should study if the temperature range can be relaxed to a moderately higher temperature without compromising cognitive performance when the head temperature can be maintained cool.

Several possible mechanisms may explain why thermal conditions affect cognitive performance [55,62]: 1) thermal comfort impacts arousal and attention; 2) temperature variation may affect physiological and health parameters; 3) thermal conditions may modify participants' emotion, motivation and effort. Therefore,



A)



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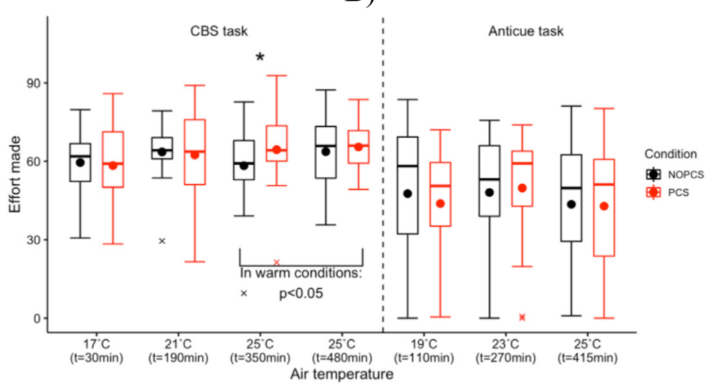
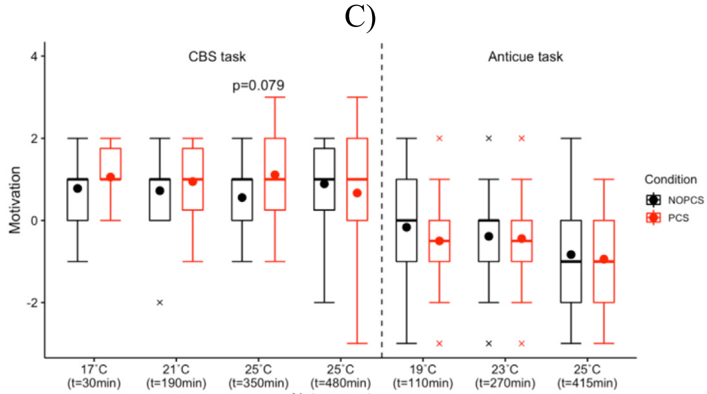


C)



D)

Fig. 11. Interactions between task and performer: A) Frustration level, B) Perceived performance (left part: perceived performance at each timepoint; right part: average perceived performance by scenario), C) Effort devoted, D) Motivation. The symbol * indicates p < 0.05, x indicates potential outliers.

Table 3
Mediation effects of variables on the relationship between scenario and task performance.

Mediators	CBS task - comprehensive score (at 25°C)	Anticue task - average RT of two cues (at 19°C)
Head skin temperature	n.s.	n.s.
Head thermal sensation	n.s.	n.s.
Hand skin temperature	n.s.	n.s.
Hand thermal sensation	n.s.	$p < 0.05$
Mean skin temperature	n.s.	n.s.
Whole-body thermal sensation	n.s.	n.s.
Whole-body thermal comfort	n.s.	n.s.
Effort	$p < 0.01$	n.s.
Motivation	n.s.	n.s.
Alertness	n.s.	n.s.
Arousal	n.s.	n.s.
Pleasure	n.s.	n.s.
Perceived air quality	n.s.	n.s.
Perceived air freshness	n.s.	n.s.

Note: n.s. stands for non-significance.

cooling the head may affect cognitive performance via those possible means. In the current study, the mediation analysis showed that improvements on the CBS task at 25°C were driven by the increase in effort invested in the task while using the PCS (Table 3). A following question is why cooling the head increased participants' effort investments. Further analysis suggested that the forehead temperature may be involved in this ($p = 0.09$, Fig. 12C). We hypothesize that an increase of effort may be related to the cooling of the orbitofrontal cortex that occupies the superficial frontal lobe region just above the orbits. The orbitofrontal cortex has been shown to have functionality in motivation[63], emotion [64,65] value perception [66], reward [67], and decision making [64,65]. Although the deep brain temperature is mainly regulated by the internal cerebral circulation, the superficial cerebral region (e.g. orbitofrontal cortex) may be susceptible to external thermal conditions [68,69]. It has been noted that almost all cerebral processes are affected by temperature variation [70]. Therefore, we postulate that head cooling affects the temperature of the orbitofrontal cortex, resulting in an influence on subjective effort investments and the CBS task performance that is sensitive to the subjective effort.

4.3. Factors influencing the effect of the PCS on cognitive performance and methodological considerations

As discussed above, the results indicate that the effects of a PCS on cognitive performance depended on task type. They also support previous literature [28,22] indicating that the effects of temperature on cognitive performance are highly task-dependent. The tasks were categorized into two types in the current study: a simple task (Anticue task) and a complex task (CBS task). This category is confirmed by the finding that the participants voted that the CBS task was more demanding than the Anticue task ($p < 0.05$, Table 1). Moreover, the complex task performance was associated with participants' effort and motivation while the simple task performance was related to subjective alertness ($p < 0.01$, Table 2).

It should be noted that the effects of the PCS on cognitive performance in cool conditions (17-21°C) was tested in a drifting temperature scenario (Figs. 6 and 7). However, the ramp imposed in the current study is a slow ramp (1.5°C/h), where the thermal perceptions would be similar to that in a static scenario [30,36]. Therefore, the effect of the PCS on cognitive performance in 17-21°C probably can be generalized to a stable temperature scenario.

On the other hand, the improved complex cognitive performance using the PCS at 25°C was observed in the later parts of the 8-h measurements (Fig. 7E), during which previous task loads may cause mental fatigue. Therefore, the observed PCS's effect may be applicable to a situation in which the participants feel mentally fatigued rather than any situation in which the thermal environment is slightly warm. However, we let the participants rest 40–60 min between two tasks assessments to avoid task-induced mental fatigue. In the PCS scenario, the participants were able to maintain their thermal comfort and the effect of the varying ambient thermal conditions among timepoints on alertness and arousal may be excluded. Thus, the stability in alertness and arousal in the PCS scenario likely indicate the absence of task-induced mental fatigue (non-significant effects of timepoint on alertness and arousal in the PCS scenario, Fig. 10). Considering the evidence, the observed PCS's benefit on complex cognitive performance could be applicable to a scenario where the thermal environment is slightly warm. It should be noted that the aim of this study is to investigate the effect of the PCS on cognitive performance. Thus, by employing a cross-over, randomized and balanced design, the fatigue effect will not have a led to a bias in the comparison of the two scenarios in any case.

In the current study, the participants were self-motivated, which applies to most office scenarios. Interestingly, concomitant improvements on cognitive performance, arousal, alertness and motivation appeared at $t = 415$ min but abruptly disappeared at $t = 480$ min (Fig. 7, Fig. 10, and Fig. 11). A likely explanation is that participants felt more excited and motivated at the end because the long-day measurement was nearly finished ($t = 480$ min). It is supported by the fact that effort, arousal, alert and motivation were higher at the end ($t = 480$ min) compared to those at $t = 415$ in the NOPCS scenario (Fig. 10 and Fig. 11). Similarly, the alertness and arousal decreased linearly with the increase of ambient temperature in the NOPCS scenario before the end ($t < 480$ min, $p < 0.05$, Fig. 10C, E) but this trend was disrupted at the end ($t = 480$ min, Fig. 10). High motivation and effort may override the effect of temperature on cognitive performance [22,55]. Therefore, there may have been little room for the PCS to improve at the end when participants were highly excited and motivated. Nevertheless, on average, the PCS enhanced the comprehensive performance on the CBS task at 25°C ($p = 0.053$, Fig. 7E) and increased participants' effort investments ($p < 0.05$, Fig. 11C).

Finally, a comparison is practically meaningful of a PCS scenario in non-neutral thermal conditions with a NOPCS scenario in neutral thermal conditions. However, this comparison is out of the scope of this study. Based on our study design, we are unable to unbiasedly analyze this comparison since the learning effects may confound it. Therefore, we suggest that future work can focus on this comparison.

5. Conclusions

This study investigated the effects of a PCS that targeted the extremities and the head, on two distinctly different cognitive task performances when participants were self-motivated. The main conclusions are as follows:

- Although the PCS did not affect thermal comfort at slightly warm temperatures (constant at 25°C, mainly cooling the head), the use of the PCS increased the average complex cognitive per-

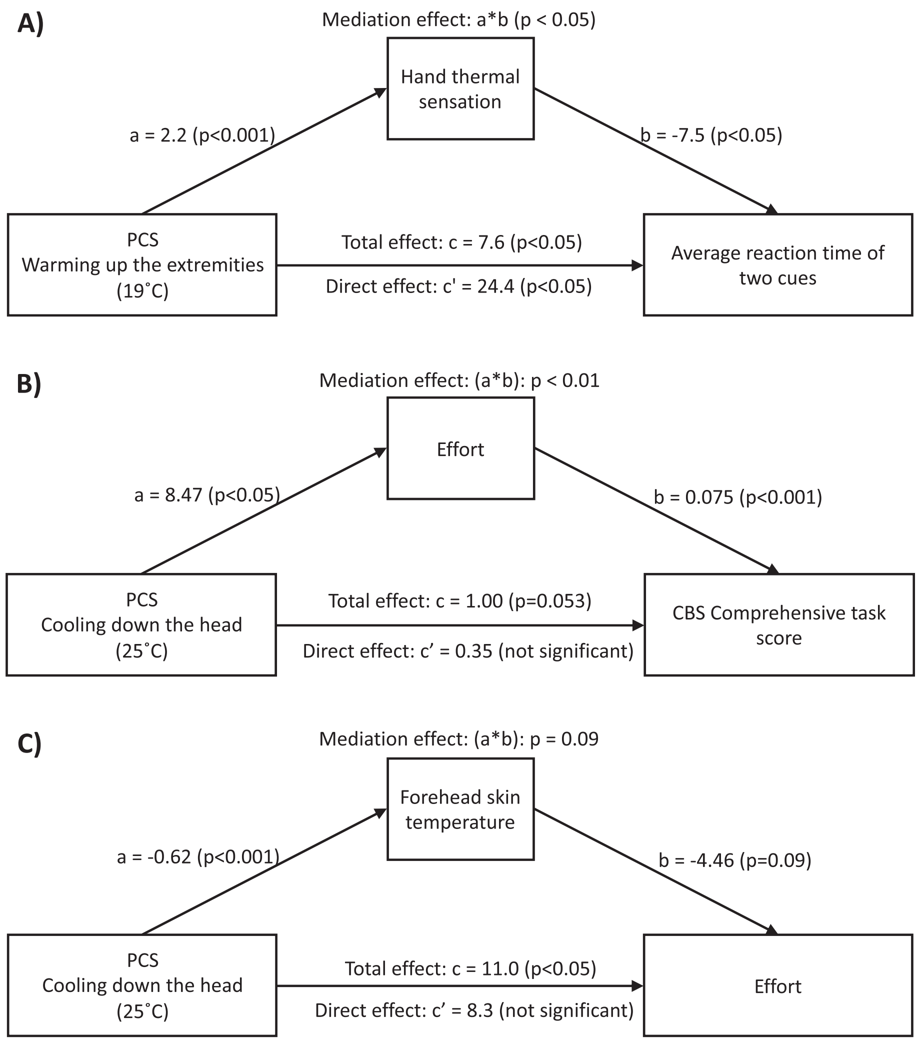


Fig. 12. Mediation paths analysis. A) hand thermal sensation mediated the effect of PCS on the Anticue task performance at 19℃, B) Effort mediated the effect of PCS on the CBS task performance at 25℃, C) Forehead skin temperature showed a trend to mediate the effect of PCS on the effort at 25℃. The arrows indicate the direction of the effect. The coefficient a indicates the effects of the PCS on the mediator. The coefficient b indicates the effects of the mediator on the outcome variable. The a*b indicates the mediation effect (indirect path). The coefficient c' indicates the direct effect of the PCS on the outcome variable besides the path through the mediator. The coefficient c indicates the total effects of the PCS on the outcome variable, including direct effects and mediation effects.

formance at 25℃ (CBS task). The results show that this improvement may stem from the increased devoted effort when cooling the head at 25℃. No significant effects were found for the simple task (Anticue task).

- Although the PCS significantly improved thermal comfort in the mild cold to neutral environments (a ramp of 17-23℃, mainly warming the extremities), no evidence was found that it enhances complex cognitive performance. On the other hand, it increased the simple reaction time (in the neutral-cue conditions of the Anticue task).
- The complex task is sensitive to effort and motivation while the simple task is sensitive to alertness.
- The PCS significantly decreased perceived physical demand at 25℃ and generally increased perceived task performance in 17–25℃.
- No significant differences in task-induced heart rate and heart rate variability were found when using the PCS.

The above results indicate that whole-body thermal comfort is not necessarily correlated with cognitive performance in spatially non-uniform conditions created by the designed PCS. The thermal state of the head, independent from its influence on thermal comfort, potentially plays an important role in cognitive performance. Selective cooling of the head can enhance complex cognitive performance in a slightly warm environment via increasing participants' effort investments. On the other hand, warming extremities in cold environments may increase the simple reaction time but will not affect complex cognitive performance.

Data availability

Data will be made available on request.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2022.112617.

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