The effects of personal comfort systems on thermal comfort, cognitive performance and thermo-physiology in moderately drifting temperatures

The Effects of Personal Comfort Systems on Thermal Comfort, Cognitive Performance and Thermo-physiology in Moderately Drifting Temperatures

Wei Luo
Maastricht University
wei.luo@maastrichtuniversity.nl

Rick Kramer
Maastricht University
rick.kramer@maastrichtuniversity.nl

Yvonne de Kort
Eindhoven University of Technology
y.a.w.d.kort@tue.nl

Pascal Rense
Maastricht University
p.rense@maastrichtuniversity.nl

Wouter van Marken Lichtenbelt
Maastricht University
markenlichtenbelt@maastrichtuniversity.nl

ABSTRACT

Strict ambient temperature control is common practice in modern office environments aiming to satisfy the thermal comfort demand of an average person: the one-climate-fits-all paradigm. However, three consequences arise: (i) Due to inter-individual differences, individuals' thermal comfort is compromised; (ii) Strict climate control results in high energy demands and therefore hinders achieving sustainability targets; (iii) Thermal resilience may decrease as people are no longer exposed to natural thermal variations. A more dynamic environment allowing more temperature variations may reduce the building energy demand substantially. However, thermal comfort may be jeopardized. Studies indicate that a Personal Comfort System (PCS) can improve thermal comfort. Most studies still apply PCS in a rather strict ambient environment, aiming at thermal comfort only. The influence of PCS in a dynamic, i.e., drifting, environment on individual thermal comfort, cognitive performance and physiology remains largely unstudied.

Therefore, preliminary results of a study on PCS in a dynamic indoor environment are presented, targeting only those body segments that are most sensitive to thermal discomfort. In this study, a personal comfort system was developed consisting of a heating desk, a heating mat and a personal fan aiming at conditioning the most uncomfortable body segments under mild cold and mild warm environments. Two equal drifting temperature scenarios were performed, with PCS and without PCS, starting at 17˚C in the morning and increasing to 25˚C in the afternoon. So far, eight subjects were enrolled, including three males and five females. Thermal perception, body temperatures and cognitive performance were measured.

The results suggest that the tested PCS can improve thermal comfort in moderately drifting temperatures. The application of PCS may not change the effectiveness of drifting temperature on vasomotion in terms of the underarm-finger skin temperature gradient. The cognitive performance can even be enhanced by the use of PCS, depending on the task and environmental temperature.

Keywords

Drifting temperatures, Personal comfort system, Health, Thermal comfort, Cognitive performance

1 INTRODUCTION

The one-climate-fits-all paradigm has been applied worldwide since the proposal of the PMV/PPD model, which was developed by P.O. Fanger [1]. The model uses a theoretical heat-balance equation, which is used via empirical study data to estimate the mean thermal sensation vote. A predicted mean vote (PMV) of a general population is calculated from six parameters: mean radiant temperature, air temperature, airflow, relative humidity, clothing and metabolic rate [1]. The recommended bandwidth of PMV ($-0.5 < PMV < 0.5$) leads to the common practice of controlling indoor temperatures in a rather small range. Three consequences arise. The first consequence is compromised individual thermal comfort. The assumption of the “average person” ignores the considerable variation of the population due to age, gender, thermal history and so on. Different individuals may require different thermal environments. A recent large-scale field study indicates that the prediction of the PMV/PPD model has a low accuracy and overestimates the discomfort outside neutral thermal environments [2]. The overall prediction accuracy of the PMV/PPD model is 34%, including the data from air conditioned, naturally ventilated and mixed mode buildings [2]. The PMV has higher accuracy near the “neutral” vote, but never more than 60% regardless of the building type [2]. The second consequence is high energy consumption. The building sector is responsible for up to 40% of the global energy consumption, of which half is associated with indoor temperature control [3][4]. The third consequence is possibly decreased thermal resilience as people are no longer exposed to naturally varying thermal environments. Staying in the neutral temperature range will impose less thermal stress on the body and therefore reduce the “exercise” of thermal regulation. Numerous studies show that regular exposure to heat and cold pre-trains the body, enables the body to adapt to its environment, increases thermal resilience, and therefore mitigates the physiological strain in hot and cold environments respectively [5][6].

The metabolic syndrome is one of the main health challenges in Europe [7]. Temperature variations may elicit important health benefits, specifically pertaining to the metabolic syndrome, as demonstrated by previous studies [8] and may reduce the building energy demand substantially. However, thermal comfort may be jeopardized. Schellen et al. [9] demonstrate that subjects were feeling less comfortable during the temperature drift in comparison to a constant temperature, but a temperature drift up to ±2 °C/h in the range of 17–25°C did not lead to unacceptable conditions. However, a personal comfort system (PCS) can compensate for thermal discomfort outside the neutral temperature range. By providing building occupants the possibility to manipulate their environments locally, the PCS possesses the potential to achieve thermal comfort at an individual level. In addition, the feeling of ‘being able to control’ may also provide positive psychological effects on thermal comfort [10]. Literature shows that a PCS can extend the comfortable temperature range down to 14°C and up to 32°C [11][12] and substantially reduce building energy consumption [13]. However, to our best knowledge, no study of a PCS was conducted in a dynamic environmental temperature and the majority focused only on thermal comfort. The individual thermal perception, cognitive performance and physiology remain largely unknown.

This study hypothesizes that applying a PCS which targets only those body segments that are most sensitive to thermal discomfort in combination with a dynamic indoor environment, maintains positive health effects of a drifting environment while thermal discomfort can be mitigated. Besides, the effects on cognitive performance were tested.

2 METHODOLOGY

2.1 Personal comfort systems

The personal comfort system was developed in collaboration with Ahrend®, a Netherlands-based company for office furniture, consisting of a heating desk, a heating mat and cooling fans. These systems are aiming at the most uncomfortable body segments under mild cold and mild warm conditions. The heating desk, heating mat and fans are designed for hands, feet and head respectively. Each device has four different settings: off, low, medium and high.

2.2 Recruitment of subjects

Thus far, eight subjects (5 females and 3 males) gave written consent before participating in this study, according to the declaration of Helsinki. All the subjects are healthy, Caucasian race, age between 18-40 year, BMI between 18 to 27.5 kg/m^2. Female participants are on contraceptive pills and were tested outside the menstrual period. Volunteers who smoke, present of Raynaud's phenomenon, possess extreme chronotype, or joined another biomedical study a month before, were excluded from the study.

2.3 Measurements

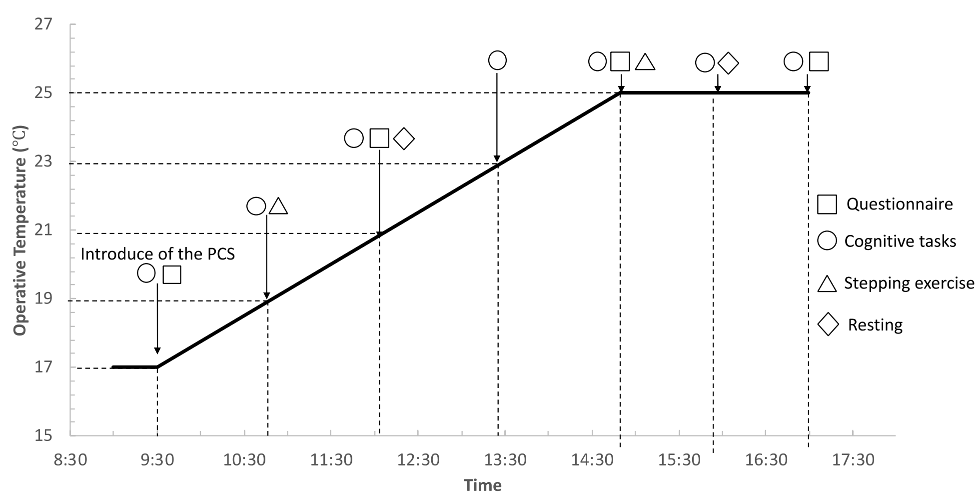
The air temperatures were measured at a height of 0.1 m, 0.6 m, and 1.1 m near the subjects. The thermal sensation and comfort were evaluated using visual analogue scales. Fourteen wireless skin temperature sensors (iButtons, Maxim Integrated Products, California, USA, Accuracy: ±0.5°C) were attached to the skin sites, according to ISO 9886 [14]. Three additional skin temperature sensors were added at the underarm, middle finger and supraclavicular to gain more insight of vasomotion [9]. The mean skin temperature was calculated using the 14-point method of ISO 9866 [14]. Four different types of cognitive tasks were employed to test four different aspects of cognitive ability related to office work, consisting of working memory, verbal ability, mental rotation and planning. All the tasks were provided by Cambridge Brain Science Inc and on the ground of classic cognitive tasks from the psychological literature [15]. For measuring working memory, a forward digital span task was adapted, which asked subjects to remember a sequence of numbers. For verbal ability, a grammatical reasoning task was used that required subjects to judge if a description matches the geometric graphs or not. For mental rotation, a spatial rotation task was used for assessing the manipulating ability of mental representations of objects by asking subjects if two pictures are the same through rotation. For planning, a Hampshire Tree task was adapted, where subjects needed to rearrange out-of-order numbered balls to a numerical order in a tree-shaped frame.

2.4 Experiment procedure

A cross-over design was performed, consisting of two conditions (with PCS condition and without PCS condition (NOPCS condition)). All the subjects finished two conditions, which were conducted on two separate days. In between the two test days was a break of at least one to a maximum of fourteen days.

The two conditions consisted of identical procedures except for the application of PCS. The procedure of testing is shown in Fig1. The subjects arrived at the lab in fasting state at 8:00 h and had standardized clothing (underwear, long-sleeve shirt, sweatpants, socks and shoes ~0.65 clo), followed by resting for one hour in a room at a constant temperature (23-25°C). Afterwards, subjects transferred to a respiration chamber for eight hours to simulate daily office work. In the respiration chamber, subjects were asked to perform office work (estimated activity level of 1.2 METs), provided with a standardized breakfast and lunch, and allowed to consume water at libitum. The temperature in the respiration room stayed at 17°C for the first half hour to let subjects inhabit to the environment. Afterwards, the PCS was introduced in the PCS condition and subjects were allowed to freely control the PCS-devices. At the same time, the temperature started increasing from 17°C to 25°C with a ramp of 1.5°C/h. The temperature remained at 25°C for two hours at the end to achieve a stable state of thermal sensation. The questionnaires were answered every two-degree of temperature rise and every hour after the temperature remained stable at 25°C. The cognitive tasks were performed every four-degree temperature rise and at the end of the test. In addition, two times 5-minute stepping exercises and 30-minute resting metabolic rate measurements (RMR) were performed. In between the measurements, they were allowed to use their computer at their desire.

Fig1 Procedure of the experiment. The indoor temperature starts to increase at 9:30 h and remain stable from 14:50 h onwards. The arrow indicates the time at which measurements took place.



A day preceding every condition, subjects got familiar with the PCS and practiced cognitive tasks to eliminate, or at least limit, possible learning effects. They were also asked to refrain from alcohol, coffee, strenuous exercise and food after 22:00 h.

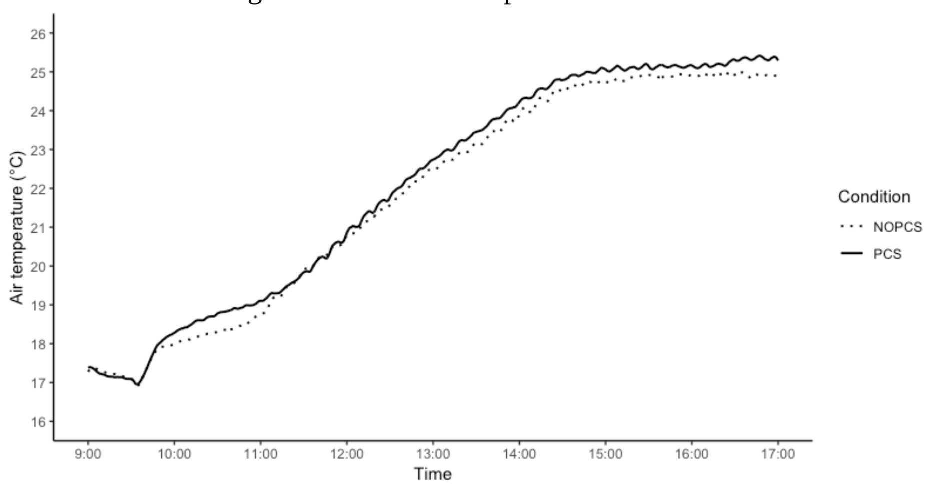
3 RESULTS

The preliminary results of the study are presented by box plots and line plots. In the box plot, the filled diamonds indicate the average value of the eight subjects. The outliers are shown as filled circles. In the line plot, the dotted curve represents the air temperature in the NOPCS condition and the solid curve that in the PCS condition.

3.1 Air temperature

Figure 2 shows the air temperature in the room. The air temperature profile complies with the designed profile in both conditions. Although the average air temperature in the PCS condition is generally higher than in the NOPCS condition, the difference (0.23 ± 0.15°C) between PCS and NOPCS condition is regarded as acceptable.

Fig 2. Measured air temperature over time

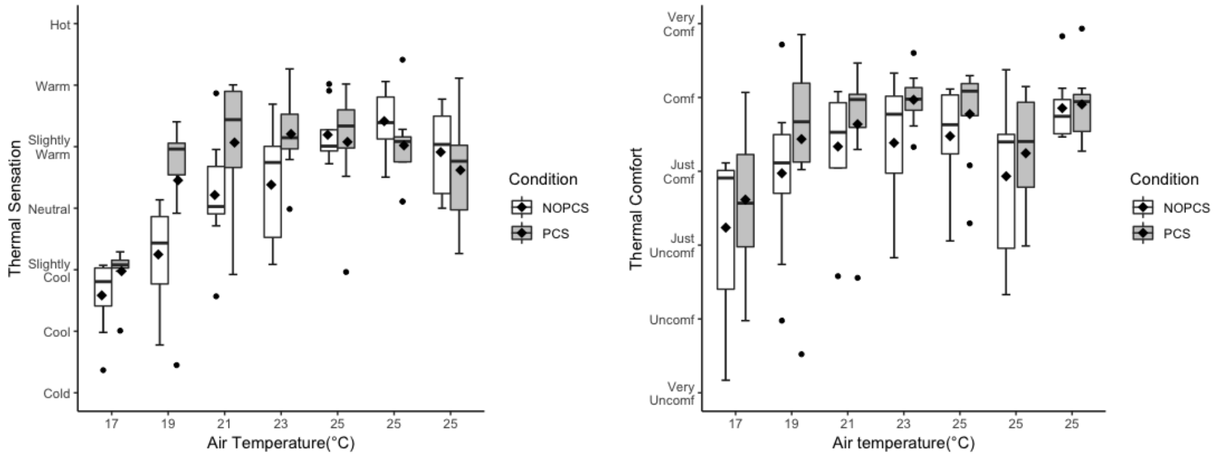


3.2 Thermal perception

Figure 3a shows box plots of the thermal sensation in the two conditions. Without PCS, the thermal sensation changes from “cool” to “slightly warm” along with the increase of air temperature. The individual difference is evident in our study as one subject vote lies between “slightly cool” and “cool” at 21°C while another one’s vote between “slightly warm” and “warm”. The average range of thermal sensation under the same temperature is 2.08±0.70. With PCS, the average thermal sensations are warmer in cold conditions and cooler in warm conditions compared to those in NOPCS. The average range of thermal sensation under the same temperature is 2.69±0.84.

The average thermal comfort vote is higher in the PCS condition comparing to the NOPCS condition (Figure 3b). In the NOPCS condition, 72% of the votes is higher than “just comfortable” while in the PCS condition this is 84% of the votes. By applying PCS, the average thermal comfort improved by 0.34±0.16.

Fig 3 Thermal perception votes *('Comf' is the abbreviation for 'comfortable'. 'Uncomf' is the abbreviation for 'uncomfortable')*



(a) Thermal sensation votes

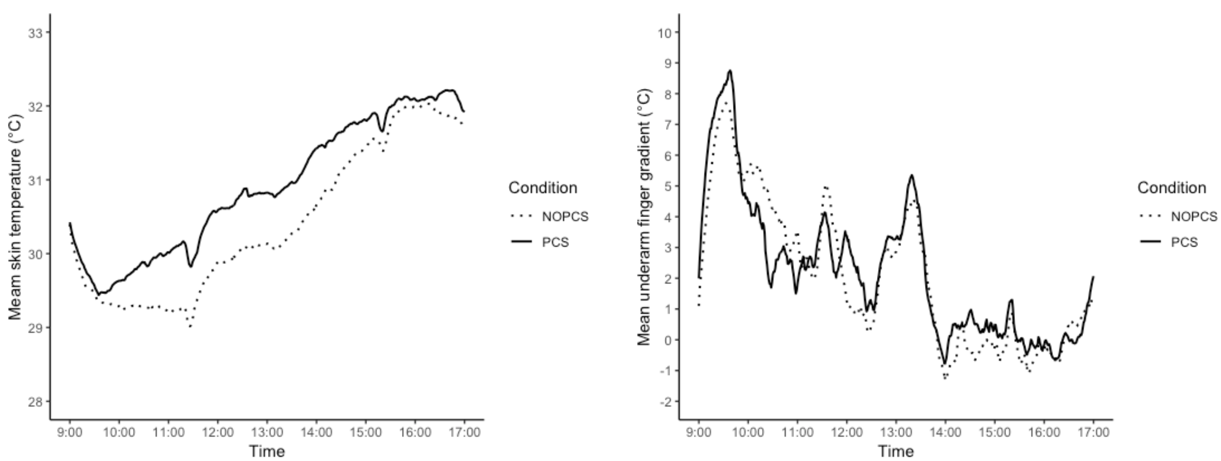
(b) Thermal comfort votes

3.3 Skin temperatures

Figure 4a presents the average of all participants of mean skin temperature over time. Mean skin temperature is an indicator of thermal sensation and an important input signal for thermoregulation. In the first half-hour, there is no obvious difference in the mean skin temperatures between the two conditions. It indicates that the habituation period makes the subjects achieve a similar thermal state in the two conditions. For the remainder of the test, the mean skin temperature in PCS condition is higher than in NOPCS condition.

Figure 4b demonstrates the gradient of skin temperature between underarm and finger, which is regarded as an index of vasomotion. There is no obvious difference between the two conditions. It seems likely that the effect of drifting temperatures on vasomotion remains when applying PCS.

Fig 4 Skin temperatures



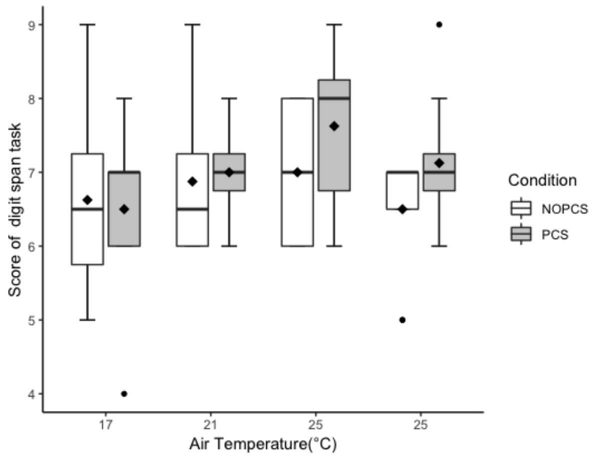
(a) Mean skin temperature

(b) Underarm-finger skin temperature gradient

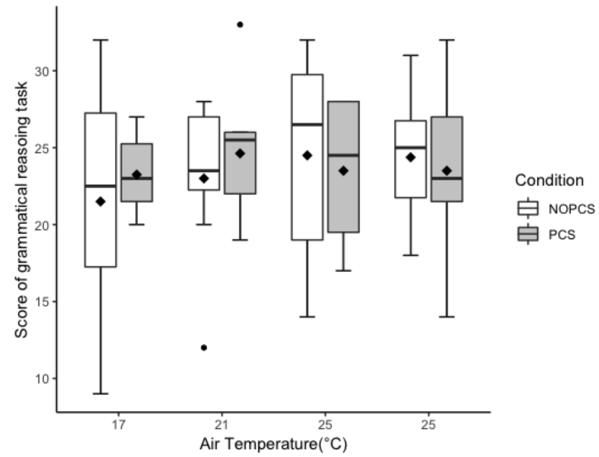
3.4 Cognitive tasks

Figure 5 illustrates the results of the cognitive performance tests. Regarding the digit span task, the PCS improved performance in the warm temperature (25°C), but the improvement was limited in the cool temperatures (17–21°C). Regarding the grammatical reasoning task, a decreased score in the warm temperature (25°C) and increased score in cool temperatures were observed, moreover, the variation is smaller using PCS at most temperatures except at 25˚C at the end of the test. Regarding the rotation task, the result was similar to the digital span, no obvious difference in mild cold and improvement in warmth. Regarding the spatial planning task, the use of PCS enhanced the performance, especially in the temperature of 21°C. And no consistent conclusion can be made in the warm temperature as the performance was improved in one while impaired in another.

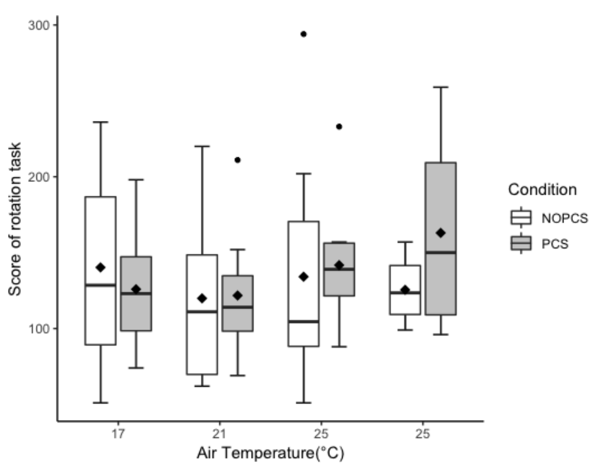
Fig 5. Cognitive tasks score



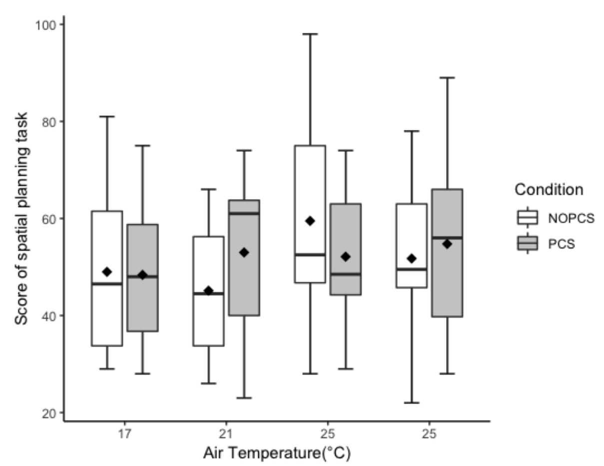
(a) Digital span task score



(b) Grammatical reasoning task score



(c) Rotation task score



(d) Spatial planning task score

4 DISCUSSION

This study tests a novel idea of PCS, which only targets the extremities: feet, hands and head. By investigating the PCS in drifting temperatures, we can see that the effect of the PCS on thermal perception is dependent on the environmental temperature. Veselý et al. [16] indicate that the thermal sensation is barely elevated by only using the heating desk or the heating mat at a temperature of 18℃. However, we found improvements in thermal sensation by warming the hands and feet together. The study of Zhang [17] complies with our finding, where thermal sensation shifts to the warm side by heating both hands and feet at a temperature of 18℃. However, the magnitude of thermal sensation change is smaller than our study, which may be due to different environmental settings imposed and equipment used. Moreover, the attenuated improvement of thermal sensation in 17℃ may indicate the limited effect of such PCS in more extreme cold environments. Surprisingly, the thermal sensation vote was lower in the PCS condition, but the mean skin temperature was higher at 25°C compared to NOPCS condition.

When leaving the paradigm of strict temperature control for a more dynamic indoor climate control in the built environment, a major concern rises whether it will decrease the daily productivity or performance. In this study, we found that the effects of PCS on cognitive performance vary among the tested temperatures and tasks. The PCS only improved the performance in warm environments when subjects were performing the digital span and rotation task. However, when performing the grammatical reasoning and spatial plan task, the PCS only enhanced performance in cool environments. This divergence may be due to the temperature affecting performance differently, depending on the task type, exposure duration and temperature [18].

So far, eight participants have been tested. Due to the small sample size, it is difficult to draw general conclusions at this moment. More participants will be tested in the near future.

5 CONCLUSIONS

This study focuses on a novel PCS, which targets only the extremities: feet, hands and the head to retain the health benefit from the dynamic environments (e.g. increased thermal resistance). The innovative insights from this study are that 1) The vasomotion reactions in terms of underarm-finger gradients were similar between the two conditions (with vs. without PCS), which indicate that the drifting temperature exercises the thermoregulatory system in a similar manner as if the PCS is in use; 2) Nevertheless, the PCS can improve thermal comfort, on average by 0.34±0.16 on a 6-point thermal comfort scale, and 84% of the comfort vote is higher or equal to ‘just comfortable’ in a dynamic environment with a moderately drifting scenario over a wide range of temperatures (17-25˚C); 3) Moreover, cognitive performance can be enhanced with PCS, but it depends on specific tasks and temperature ranges: the digital span and rotation tasks improved in a relatively warm environment (25˚C) while grammar reasoning was enhanced in a cold environment (17-21˚C). The results suggest that the tested PCS, in combination with drifting ambient temperatures, has the potential of creating a comfortable and healthy office environment, however, it is worth conducting further research to draw general conclusions.

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