The effects of novel personal comfort systems on thermal comfort and thermophysiology

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Abstract. Allowing more indoor temperature variations may stimulate human physiological thermoregulation and benefit (metabolic) health. However, thermal comfort may be compromised. To investigate possible solutions for balancing thermal comfort and health, we evaluated a novel personal comfort system (PCS) in moderately drifting ambient temperatures (17-25˚C). This PCS targets the most sensitive body parts (hands, underarms and feet in cold and the head in warm conditions), leaving the rest of the body exposed to the ambient dynamic temperature. A cross-over, randomized study was conducted in an office-like laboratory. Eighteen participants (nine male and nine female) were enrolled and performed two scenarios on separate days, one with the PCS and another scenario without the PCS in 17-25˚C. Skin temperature, skin blood flow and thermal perception were measured. The skin temperature is used to indicate thermoregulation as it is an important driver for thermoregulation while skin blood flow indicates vasomotion. The results show that the designed PCS significantly affected the skin temperature of targeted body parts while it had no significant effects on the skin temperature of most non-targeted body parts. Moreover, the skin blood flows of the hands and feet were not affected by the designed PCS in 17-21˚C. On the other hand, the designed PCS significantly changed thermal sensation and improved thermal comfort in cold to neutral conditions (17-23˚C). Therefore, the PCS may maintain the effectiveness of the cold temperature drift on vasomotion and thermoregulation, while significantly improving thermal perceptions. These findings imply that the designed PCS, combined with cold ambient conditions, potentially balances thermal comfort and health in office environments.

Keywords. personal comfort systems, thermal comfort, thermophysiology, health, drifting temperatures
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1. Introduction

One of the main health concerns worldwide is the metabolic syndrome. The prevalence of the metabolic syndrome has been suggested to be associated with temperature exposures [1–3]. For example, diabetes incidence appears to be positively related to the ambient temperature [3]. One of the possible reasons for the association between metabolic syndrome and temperature is that residing mostly in a thermal neutral condition indoors minimizes thermogenesis, in combination with other factors, contributing to obesity [4,5]. On the other hand, excursions outside the neutral temperature range may elicit important (metabolic) health benefits. Firstly, exposure to cold conditions and warm conditions increases human metabolism [6,7], beneficial for preventing or combatting overweight. Moreover, regularly activating human thermoregulation in mild cold and warmth improves insulin sensitivity and reduces the risk of cardiovascular diseases [8]. Humans spend 80-90% of their time indoors. Thus, using indoor temperature variations to stimulate human thermoregulation may be a viable way to enhance human metabolic health.

Indoor temperature design should, however, meet occupants' thermal comfort as well. The practice of indoor temperature variation is challenging because it may induce thermal discomfort. Furthermore, thermal discomfort also drives people's behaviour to reduce healthy thermal stimuli. However, recent advances in the insight in thermal comfort research may provide some potential solutions. Previous studies have shown that a moderately drifting temperature (17-25˚C with a temperature ramp around ±2 °C/h) can exercise thermoregulation without leading to thermally unacceptable conditions [9,10]. In addition, a personal comfort system (PCS) can extend the comfortable ambient temperature range down to 14°C and up to 32°C [11,12]. The PCS heats/cools body segments locally (e.g. hand, feet and torso) and allows personal control, thus, it potentiates offering individual thermal comfort. Most essentially, the PCS may precisely target the most sensitive body parts that cause thermal discomfort while leaving the rest of the body exposed to the dynamic ambient temperatures, and hence, activate thermoregulation. Taken together, a drifting temperature and/or a PCS may balance thermal comfort and thermoregulatory activation in office environments.

To date, most PCS studies focus on thermal comfort and were conducted in a stable ambient thermal environment. Given the potentials as outlined above, it is worthwhile to investigate the effect of a novel PCS on thermal comfort and thermophysiology in a drifting temperature. It was previously reported that extremities are the most uncomfortable body parts in the cold whereas the head is the most sensitive body part in warm conditions [13]. Thus, a PCS design that targets those local body parts being most uncomfortable may induce a large improvement in whole-body thermal comfort. Meanwhile, this PCS design only conditions small body areas (hands, feet and head), therefore, it may retain thermal stimulations to the rest of the body (i.e. the torso). The combination between a drifting ambient temperature profile and the designed PCS may provide a solution for the future to create a healthy and comfortable environment.

In this study, we tested a novel PCS for an office context that targets only the extremities and head under drifting ambient temperatures (17-25˚C). Thermophysiology and thermal comfort were measured. Skin temperature was used to indicate thermoregulation as it is an important driver for thermoregulation.

2. Methods

2.1 Personal comfort system

To warm the extremities in cold conditions and cool the head in warm conditions, a PCS was developed, consisting of a heating feet mat, a heating desk and two personal fans. The participants were able to adjust each device to four levels: off, low, medium and high.

2.2 Study design

Eighteen participants were enrolled (nine males and nine females) and completed two 8-hours scenarios on two separate days (with-PCS scenario and no-PCS scenario). The sequence of the scenarios was randomized. The experimental procedures of the two scenarios were identical, except for the availability of the PCS.

During the test days, the participants wore standard clothing (0.8 clo) and multiple sensors that measure skin temperature and skin blood flow. Afterwards, the participants rested in a thermally neutral condition for 30 min. Based on ISO 9886 [14], skin temperatures were assessed on fourteen sites by wireless thermometers (iButtons, Maxim Integrated Products, California, USA, Accuracy: ±0.5°C). The skin blood flows were gauged at the dorsal site of the left hand and feet by laser doppler flowmetry (PF5000, Perimed AB, Sweden).

The participants were transferred to a climate chamber around 9:00 h, where a drifting temperature profile was applied (Fig. 1). First, the temperature remained at 17˚C for 30 min to habituate participants to the environment. Then, the ambient temperature increased from 17˚C to 25˚C at a rate of change of 1.5˚C/h. Meanwhile, the participants were able to control the PCS freely in the with-PCS scenario. Every 2˚C rise, the participants did a measurement, including keeping still for 5 min to measure skin blood flow and filling in a questionnaire to rate their thermal perceptions. For thermal perceptions, thermal comfort and thermal sensation were assessed using visual analogue scales according to ISO standard 10551 [15]. Once the temperature reached 25˚C, it was maintained at 25˚C for 130 min and measurements were completed every 65 min. In total, participants resided in the climate chamber for 8 h. Participants' activities and food intake were standardized.

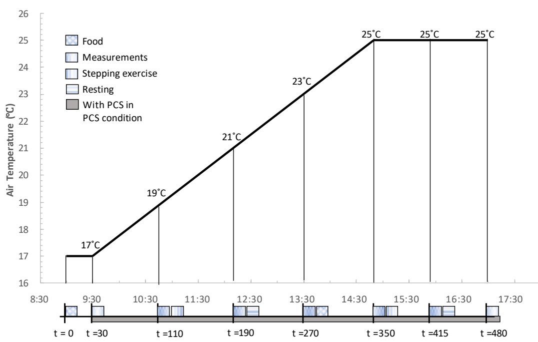

Fig. 1 – Protocol of the scenarios (the figure is adopted from [16])

2.3 Data analysis

The skin temperature was continuously monitored. Thus, the data of 10 min before submission of the questionnaire were averaged as a representative value. For skin blood flow, the average of 5 min keeping still data was used. The differences between the two scenarios were tested using a linear mixed effects model, with participant as a random factor, and the scenarios and timepoint as fixed factors. The significance level was set at 0.05.

3. Results

3.1 Thermal perceptions

The thermal comfort and sensation data have been previously reported [16]. In the NOPCS scenario, there was a steady rise in thermal sensation from 17˚C to 25˚C and it generally followed the temperature profile (Fig 2). The thermal comfort increased in 17-21˚C and levelled off afterwards in the NOPCS scenario (Fig 3). In comparison to the NOPCS scenario, the PCS significantly increased thermal sensation in cold to neutral conditions. Also, thermal comfort significantly improved. In warm conditions (25˚C), no significant thermal perception difference between the two scenarios was found.

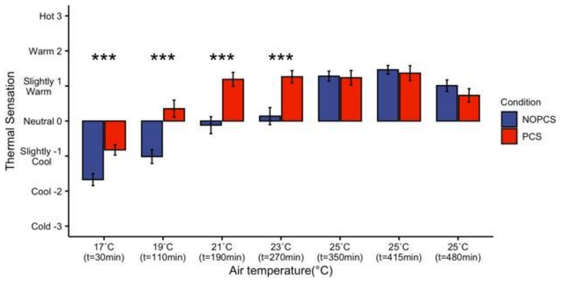

Fig. 2 – Thermal sensation votes over time (the data were adopted from [16]. *, **, *** indicate p<0.05, p<0.01, p<0.001 respectively.)

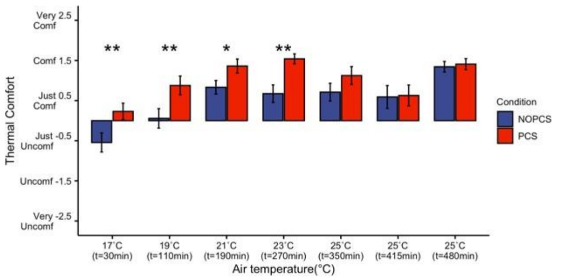

Fig. 3 – Thermal comfort votes over time (the data were adopted from [16]. *, **, *** indicate p<0.05, p<0.01, p<0.001 respectively.)

3.2 Skin temperatures

In cold to neutral conditions, the participants mainly manipulated the heating desk and heating feet mat. The PCS significantly increased skin temperature of the targeted body parts in 19-23˚C while no significant differences were found at 17˚C (hand, underarm and feet, Table 1). For most non-targeted body parts (head, neck, upper arm, torso, upper leg), the use of the PCS did not affect the skin temperature (Table 1). On the other hand, the skin temperature of the lower leg was significantly higher in the PCS scenario (19-23˚C, Tab. 1).

At 25˚C, the personal fan was generally used to cool the head region. As expected, the PCS successfully cooled the head and neck (Table 2). However, feet and lower leg skin temperatures were higher in the PCS scenario at 25˚C, t = 350min and t = 415 min (Tab. 2). For other non-targeted body parts (upper arm, underarm, hand, torso and upper leg), the skin temperatures were unaffected by the PCS.

Table 1 – Significance levels of the skin temperature differences in local body parts between two scenarios in 17-23˚C (X, *, **, *** indicates p>0.05, p<0.05, p<0.01, p<0.001 respectively. ↑/↓ indicates a higher/lower skin temperature compared to the NOPCS scenario.)

	17˚C (t=30)	19˚C (t=110)	21˚C (t=190)	23˚C (t=270)
Head	X	X	X	X
Neck	X	X	X	X
Upper arm	X	X	X	X
Under arm	X	↑, ***	↑, ***	↑, ***
Hand	X	↑, ***	↑, ***	↑, **
Torso	X	X	X	X
Upper leg	X	X	X	X
Lower leg	X	↑, **	↑, *	↑, **
Feet	X	↑, ***	↑, ***	↑, ***

Table 2 – Significance levels of the skin temperature differences in local body parts between two scenarios at 25˚C (X, *, **, *** indicate p>0.05, p<0.05, p<0.01, p<0.001 respectively. ↑/↓ indicates a higher/lower skin temperature compared to the NOPCS scenario.)

	25˚C (t=350)	25˚C (t=415)	25˚C (t=480)
Head	↓, ***	↓, ***	↓, ***
Neck	↓, **	↓, ***	↓, **
Upper arm	X	X	X
Under arm	↑, ***	X	X
Hand	X	X	X
Torso	X	X	X
Upper leg	X	X	X
Lower leg	↑, ***	↑, **	X
Feet	↑, ***	↑, **	X

3.3 Skin blood flow

The skin blood flows of the hands and feet showed different patterns in the NOPCS scenario (Figures 4 and 5). The hand skin blood flow increased with the rise of ambient temperature (Fig. 4). In contrast, the feet skin blood flow remained stable across 17-23˚C, but showed an increase at 25˚C (Fig. 5). Overall, the PCS did not significantly affect the skin blood flow of hands and feet, except for a rise in hand skin blood flow using the PCS at 23˚C.

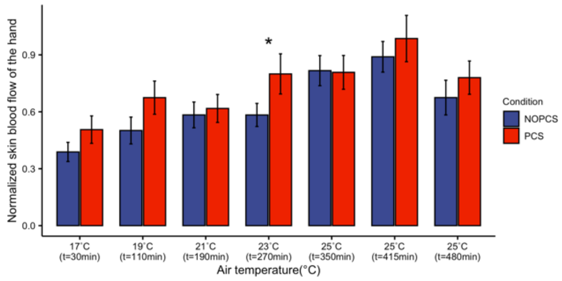

Fig. 4 – Normalized skin blood flow of the hands over time (the data were adopted from [16]. *, **, *** indicate p<0.05, p<0.01, p<0.001 respectively.)

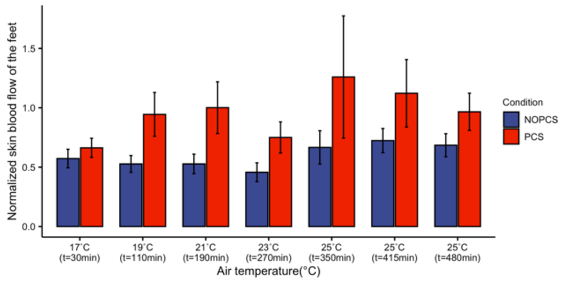

Fig. 5 – Normalized skin blood flow of the feet over time (*, **, *** indicate p<0.05, p<0.01, p<0.001 respectively.)

4. Discussion

The purpose of this study was to determine the effect of a novel PCS on thermophysiology and thermal comfort under drifting ambient temperatures. We found that thermal perceptions were significantly improved using the PCS in 17-23˚C (Fig. 2 and 3, [16]). The PCS significantly manipulated the skin temperature of targeted body parts, but it did not affect non-targeted body parts in most cases (Tables 1 and 2). Moreover, the skin blood flows of the hands and feet were generally similar between the two scenarios (Fig. 4 and 5).

By targeting the most sensitive local body parts, the PCS successfully improved thermal comfort in 17-23˚C. This improvement is comparable to Zhang's study [17], where the participants also felt more comfortable by heating hands and feet at 18˚C. Given the fact that the designed PCS only cooled/heated a small area of the body (extremities or the head area), it was assumed that the non-targeted body segments would not be influenced by the PCS. The present results validate this assumption. The PCS did not affect the skin temperature of the major non-targeted body segments. This finding was also reported in other studies [18,19]. Interestingly, the PCS significantly increased the skin temperature of the lower leg in 17-23˚C. The reason may be that the heating mat caused an unintentional elevation of the ambient temperature near the lower leg. Moreover, the increased skin temperature of the lower legs and feet in the PCS scenario continued until 25˚C. This may be attributed to the fact that some participants still used the feet heating mat at 25˚C.

Skin temperature feeds an important signal to our brains used for thermoregulation [20]. Considering that skin temperatures of non-targeted body segments were similar between the two scenarios in most cases, we can reasonably assume that the thermoregulatory responses were also similar between the two scenarios. The present results confirm this. Indeed, there were no significant differences in hands and feet' skin blood flow. This indicates that vasomotion, one of the thermoregulatory responses, remained unchanged when using the PCS. In general, it seems that the designed PCS did not reduce the effectiveness of the cold temperature drift on thermoregulation and vasomotion.

5. Conclusion

In this study, the effects of a novel PCS on thermophysiology and thermal comfort were studied. The main conclusions are that: 1) the designed PCS significantly improved thermal comfort in cold to neutral conditions [16]. 2) the designed PCS did not affect the skin temperature of non-targeted body parts in most cases. 3) The PCS did not generally affect vasomotion indicated by the unchanged skin blood flow of the hands and feet. These findings suggest that the designed PCS has a great potential to balance thermal comfort and health under cold ambient conditions in office environments.

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7. Data availability statement

The data that support the findings of this study are available from the corresponding author, [W.L.], upon reasonable request.

8. References

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