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Creating alliesthesia in cool environments using personal comfort systems

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Abstract:

Personal Comfort Systems (PCS) promise to reduce the energy needed to condition indoor environments, while also enhancing their occupants' thermal pleasure. To explore these potentials in heating conditions, we compared the effectiveness of PCS heating various portions of the occupant against the normal Air Conditioning (AC) practice of warming the room volume. Twenty subjects experienced three modes of heating (AC only, AC together with PCS, and PCS only) at three initial room air temperatures (14, 16, and 18°C) and were given some control options throughout the testing. Skin temperatures, thermal pleasantness, and thermal sensation votes were recorded during the exposures. The PCS heating was more effective than AC control at alleviating occupant discomfort. With PCS present, the three initial room temperatures produced equivalent positive perceptions of thermal pleasantness and sensation. Providing occupants with AC control did not influence this result. AC alone did not produce appreciable alliesthesia due to its slow rate of changing the room temperature. In contrast, PCS produced an immediate pleasantness experience with its faster-acting conductive and radiative heating spread non-uniformly across the body. Whole-body thermal pleasantness closely followed the pleasantness of local body parts experiencing thermal stimuli. These temporal and spatial characteristics give PCS a significant advantage in generating thermal pleasure over traditional AC systems.

Keywords: Personal comfort system; Local heating; Thermal perception; Thermal pleasure; Alliesthesia

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1. Introduction

1.1 Personal Comfort Systems

Personal Comfort Systems (PCS) is a general term for a category of low-energy thermal comfort devices designed for targeted local cooling or heating of building occupants [1]. PCS are energy efficient because the heating or cooling is targeted on occupants rather than the ambient space, and they provide better comfort because they can be controlled by the occupants based on their needs. Field studies of PCS have reported reductions in Heating, Ventilation and Air Conditioning (HVAC) energy use resulting from widened temperature deadbands, and also improved occupant thermal comfort [1-4]. The potential for PCS to reduce the carbon footprint of buildings is reflected in their recent codification into dominant comfort standards [5]. They have a promising role in alternative cooling and heating strategies, such as using fans for low-energy cooling in summer [6], and foot warmers in office buildings in winter [2].

Many researchers have investigated PCS for cooling or heating occupants. For heating in cool environments, there are heated chairs [4, 7-12]; footwarmers [2, 9]; lower body part heating [13] (deployed under-table via warm airflow); and traditional local heating systems (named Huo Tong [14] and Huo Xiang [15]) in south China. One method of evaluating the effects of PCS is the Corrective Power (CP) metric. CP is defined as the difference between two ambient temperatures at which equal thermal sensation is achieved – one with no PCS (the reference condition), and one with PCS in use [1]. CP represents the degree to which a PCS system may "correct" the ambient temperature toward neutrality. Footwarmers created a CP value of 2.2 K in a field study [2]. A heated chair created CP values from 0.56 – 2.8 K in another field study [3], where the different CP values correspond to different study periods in which the room temperatures were adjusted at different levels. PCS are also able to improve occupant thermal comfort. In a 6-month field study providing a heated and cooled chair for 40 occupants [4], the satisfaction with the chair reached 97%. During this period, occupants used either the heating or cooling functions of the chair for 77% of the time they were seated.

A meta-analysis of PCS studies [1] summarized in Fig. 1 identified seven studies in which higher levels of comfort occurred with PCS than under the uniform neutral reference environments observed in those studies; no studies were found showing the opposite effect (the seven studies are cited in the caption of the figure). The indoor temperatures associated with the PCS tests ranged from 16 °C to 28 °C. Much of the high occupant comfort found with PCS devices comes from their ability to provide bespoke thermal environments catered to individual preferences. In addition, proximal positioning in PCS ensures more rapid delivery of thermal stimuli to occupants compared to conventional air conditioning systems. These advantages, paired with the ability to target body sites that are significant for comfort, make PCS the ideal solution for leveraging an emerging framework of thermal perception in dynamic environments - known as thermal alliesthesia - for moderate indoor conditions.

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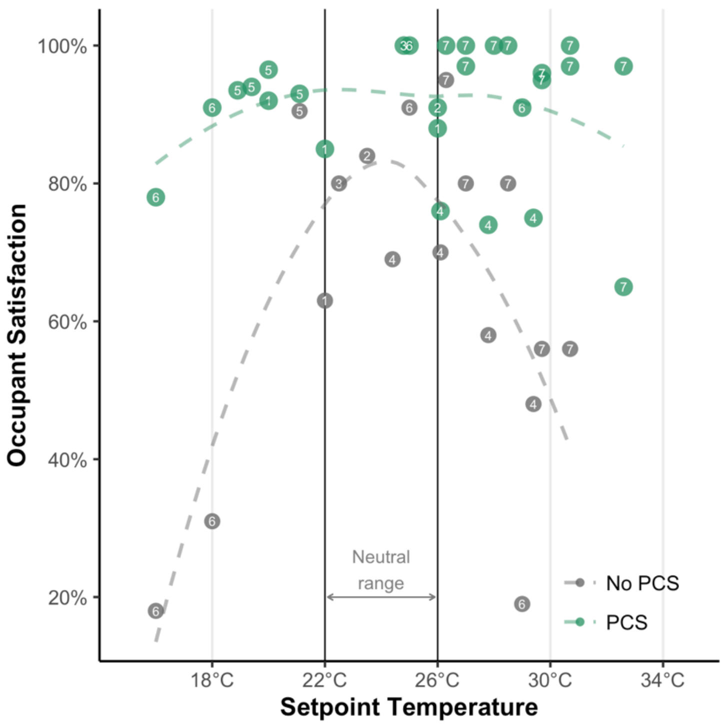

Fig. 1. A meta-analysis of seven studies showing higher thermal satisfaction levels achieved by PCS (green) compared to conditions without PCS (grey). Solid lines mark the typical neutral temperature range (22 to 26°C). Modified after reference [1]. The 7 studies are: 1 - [7], 2 - [16], 3 - [17], 4 - [18], 5 - [2], 6 - [8], and 7 - [19].

1.2 Thermal pleasantness (alliesthesia)

Alliesthesia refers to the pleasure response (or pleasantness) that accompanies the correction of thermal imbalances across body sites [20, 21]. It is typically broken down into two distinct types: 1) temporal alliesthesia is the pleasure arising from whole-body changes in skin and/or core temperatures that correct a global thermal imbalance [22, 23], and 2) spatial alliesthesia occurs when local stimuli counter the thermal state of the rest of the body e.g., warming particular sites on an otherwise cool body surface [24-27]. Thermal pleasure in both of these types is driven by the heightened response of the thermosensory system to the rate-of-change of skin temperature compared to the absolute temperature [28].

Temporal alliesthesia was investigated through a series of experiments on 13 subjects in transitional environments [21]. A rapid change of pleasure occurred when subjects switched from one condition to another. A peak of pleasure appeared when subjects transitioned from a cool/warm state to neutrality, while a sudden drop of pleasant sensation appeared when transitioning from neutrality to non-neutrality. Nonetheless, temporal alliesthesia is somewhat limited because an overshoot of thermal pleasure is short-lived at the onset of thermal stimuli. For spatial alliesthesia, certain combinations of thermal sensation from non-neutral body parts can produce a more pleasant sensation than that of uniform whole-body neutrality [29]. The local thermal sensation and comfort models [30-32] indicate that overall comfort or discomfort are determined by perceptions of local body parts experiencing the strongest (dis)comfort. Further, a series of

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experiments on 53 subjects with constant foot- or hand-heating [33] found that sustained heating alliesthesia was more likely to occur for individuals who had a general preference for warm conditions.

The body's thermal conditions are reflected in local skin temperatures, which are sensed by warm and cool thermoreceptors in the skin. A physiological response is initiated when skin temperatures are offset from their typical neutral value commensurate with the magnitude of deviation. In the case of moderately cold environments, the physiological response is primarily the reduction of heat loss from the extremities through vasoconstriction. This reduces extremity skin temperatures and leads to displeasure. Under the alliesthesia framework, applying corrective heat to vasoconstricted or cold-sensitive areas of the body elicits thermal pleasure. For this reason, PCS are ideally suited to leverage alliesthesia due to their ability to target corrective stimuli to particular body sites in moderate indoor environments.

The pronounced perceptual response of thermoreceptors to rapid changes in skin temperature, often referred to as an 'overshoot', is a key characteristic of thermal alliesthesia. Central heating systems (like HVAC) are disadvantaged at eliciting alliesthesia because of their slow changes of operative temperatures. By comparison, the focused heat transfer modes of PCS (conduction, focused radiation, forced convection) can trigger this overshoot effect to rapidly shift thermal perception. It is possible to coordinate perceptual overshoot with thermal changes occurring in the building [1, 34-38] to provide corrective changes using PCS. In addition, PCS can maintain steady-state skin temperature differences among local body parts to create spatial alliesthesia [33]. These attributes are simply not available to central heating systems as they are designed to keep room conditions as uniform as possible.

The higher level of occupant satisfaction experienced in the neutral temperature range with PCS compared to HVAC alone demonstrates the potential of this approach in conditions typical of office buildings. Furthermore, alliesthesia offers a promising framework to understand occupants' psychophysiological response to PCS heating/cooling [39]. It provides a basis for the parameterization of PCS design solutions to deliver enhanced occupant comfort while minimizing HVAC energy use.

1.3 Study aims

For the heating context, some critical questions about alliesthesia and PCSs remain unanswered:

1. Although PCS can generate pleasantness through local heating, room heating is still the most common way of conditioning indoor environments. Indoor occupants have the ability to control their indoor environments through thermostats of HVAC systems. It is unclear if there is a difference in pleasantness achieved with PCS alone compared to an individually-controlled room heating system.
2. The reviewed literature demonstrated the ability of PCS to maintain or improve thermal comfort across a range of ambient air temperatures. Less is known about PCS and thermal pleasantness, which might vary under different ambient air temperatures. It is important to understand the range of ambient air temperatures at which a PCS device can effectively induce thermal pleasantness, and to compare the thermal pleasantness under various ambient air temperatures.

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3. Few studies have explored the physiological responses (e.g. skin temperatures) to PCS that correspond with thermal pleasure (or alliesthesia). This relationship between physiology and perception is needed to understand how local thermal stimuli influence whole-body pleasantness.

We tested subjects' responses to a set of PCS heating devices under a series of room temperatures to fill the above-stated gaps and help advance the development of PCS heating devices for use in office buildings. Specifically, skin temperatures and thermal pleasantness were measured under individually-adjustable HVAC and PCS to compare the difference in pleasantness created by uniform and non-uniform heating. User-controlled room temperatures and pleasantness responses were compared to identify the range of ambient air temperatures that PCS devices can effectively deliver enhanced thermal pleasantness. Finally, the local and whole-body pleasantness under different conditions were explored to understand how overall thermal perception is influenced by local thermal stimuli.

2. Methodology

2.1 Facility and subjects

The experiment was conducted at Hunan University in winter (Nov - Dec) 2018. Testing was done in an office room (length × width × height = 4.5 m × 3.4 m × 3.4 m) on the third floor of a university building. The room had a split air conditioner (shortened hereafter to 'AC') operated via remote control, and a small ventilation fan installed near the window to provide fresh air. Adjacent to the test room (termed 'Room B') was an antechamber (termed 'Room A') in which subjects were acclimatized prior to testing.

A single workstation located in the center of Room B was equipped with five PCS heating devices: foot-warmer, heated seat cushion, neck-warmer, contact hand-warmer, and radiant hand-warmer (see Fig. 2). Their maximum power ratings were 80, 23, 40, 12.5, and 40 W, respectively. The foot-warmer, neck-warmer, and radiant hand-warmer used incandescent light bulbs as fast-acting radiation sources, and the heated seat cushion and contact hand-warmer used resistance heating wires arrayed under a fabric layer as contact sources. Each PCS device had a continuous controller by which users could adjust the heating power. These particular devices were intended to maximize the alliesthesia response. In practice, the contact hand heating would likely occur through a heated keyboard and heated digital mouse [40], and possibly a heated area on the desktop surface. A more powerful radiant hand-warmer would be deployed in the vicinity of the keyboard and mouse for heating hands. Since employees would usually put their hands on the table to use a keyboard and mouse, the contact or radiant hand heating will not interfere with their ability to work.

Twenty university students (ten males and ten females) aged 22±1.0 were recruited as subjects. Their height and weight were 169.2 ± 7.0 cm and 59.6 ± 9.7 kg, respectively. Each subject wore a long underwear top (0.20 clo), thin long-sleeve sweater (0.25 clo), jacket (0.36 clo), trousers (0.24 clo), ankle socks (0.02 clo), and shoes (0.02 clo). The total clothing insulation was estimated at 1.1 clo based on the clothing checklist in ASHRAE Standard 55-2020 [5].

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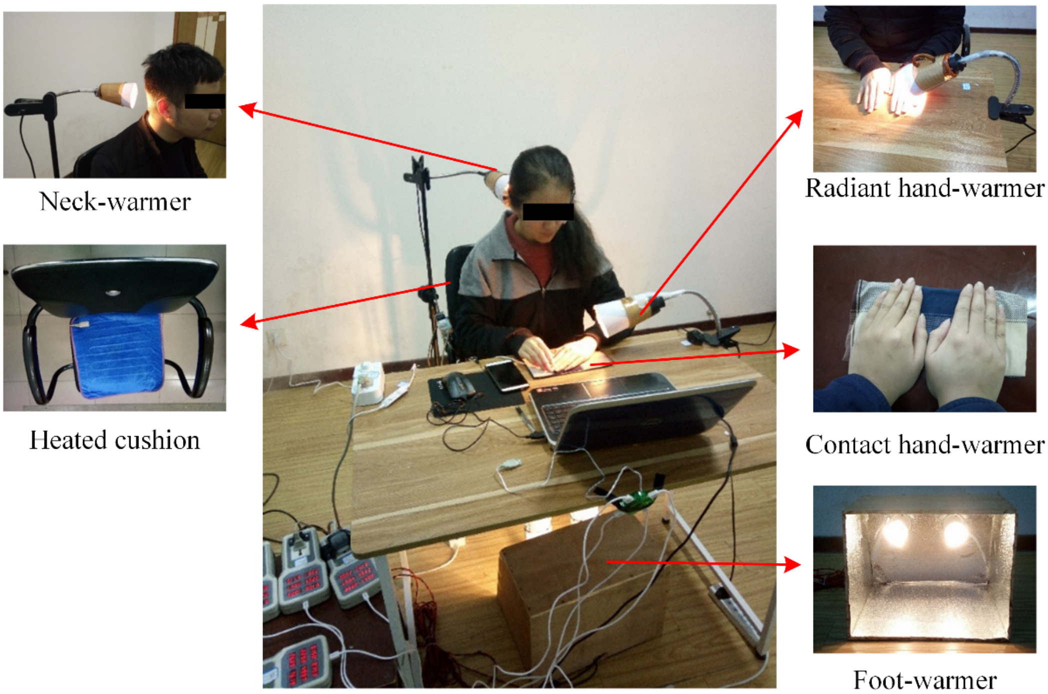

Fig. 2. Heating PCS devices used in the study. Clockwise from top left: neck-warmer, radiant hand-warmer, contact hand-warmer, foot-warmer, and heated cushion. Each PCS had a controller to regulate heating power; an example can be seen in the main picture as a white box on the edge of the table.

2.2 Procedure

The experimental design included three modes of heating control: (1) adjustable room AC only, (2) adjustable AC together with adjustable PCS, and (3) adjustable PCS only. Each of the three control modes was tested under three starting room temperatures: 14°C, 16°C, and 18°C. The PMV values for the room temperatures of 14°C, 16°C, and 18°C are approximately -2.0, -1.5, and -1.0 respectively [41]. The three PMV values were chosen for two reasons: 1) to detect the efficacy limit of PCS warming, and 2) to determine how much the intensity of resulting thermal pleasure depends on the cooling stimulus from the ambient environment on the whole-body. In total there were 9 test conditions as described in Table 2. Tests focused on one heating control mode and lasted 66 minutes: 20 minutes acclimatizing in Room A and 46 minutes testing in Room B.

Table 2. Test conditions with different initial room temperatures and combinations of adjustable AC and PCS.

Condition	Mode	Initial room temp. (°C)	Adjustable AC	Adjustable PCS
1	1	14	Yes	No
2	1	16	Yes	No
3	1	18	Yes	No
4	2	14	Yes	Yes
5	2	16	Yes	Yes
6	2	18	Yes	Yes

7	3	14	No	Yes
8	3	16	No	Yes
9	3	18	No	Yes

The experiment was designed to compare the relative effectiveness of PCS and AC control in providing pleasure, and to test whether subjects' control actions would differ for single versus combined control. The procedure for the three modes is shown in Fig. 3. Because subjects arrived at the experimental site with different thermal states from their mode of travel and the outdoor environment to which they were exposed, subjects sat in Room A at 20 °C for 20 min to neutralize their thermal state before starting the formal testing. Considering the relatively high metabolic rate of subjects (walking can be over 1.5 met) upon arrival, the ambient air temperature of Room A at 20°C approximated the neutral temperature for their clothing and activity level (see Section 2.1) based on the PMV model [41]. It is also common for winter setpoint temperatures in China to be 20 °C [42]. After acclimation, subjects moved to Room B which was conditioned to one of the three starting ambient air temperatures (14°C, 16°C, and 18°C). They were first exposed to the initial ambient air temperature for 10 minutes. The 10 min duration was determined because sedentary people's responses can become stable within 10 min after moving from one room to another [43]. Then subjects were given control over the room AC and PCS in Room B according to the following rules:

- Mode 1, where subjects could control only AC: after the first 16 min being exposed to the initial cool ambient air temperature, the subjects started to control the AC at the 36th min.
- Mode 2, where subjects could control both AC and PCS: after the first 10 min being exposed to the initial ambient air temperature, subjects started to use PCS for 6 min. They then were allowed to control the AC at the 36th min of the test, as in Mode 1.
- Mode 3, where subjects could control only PCS throughout the entire test: subjects started to use PCS at the 30th min, as in Mode 2. The room remained at the fixed set-point indoor temperature until the end of the test.

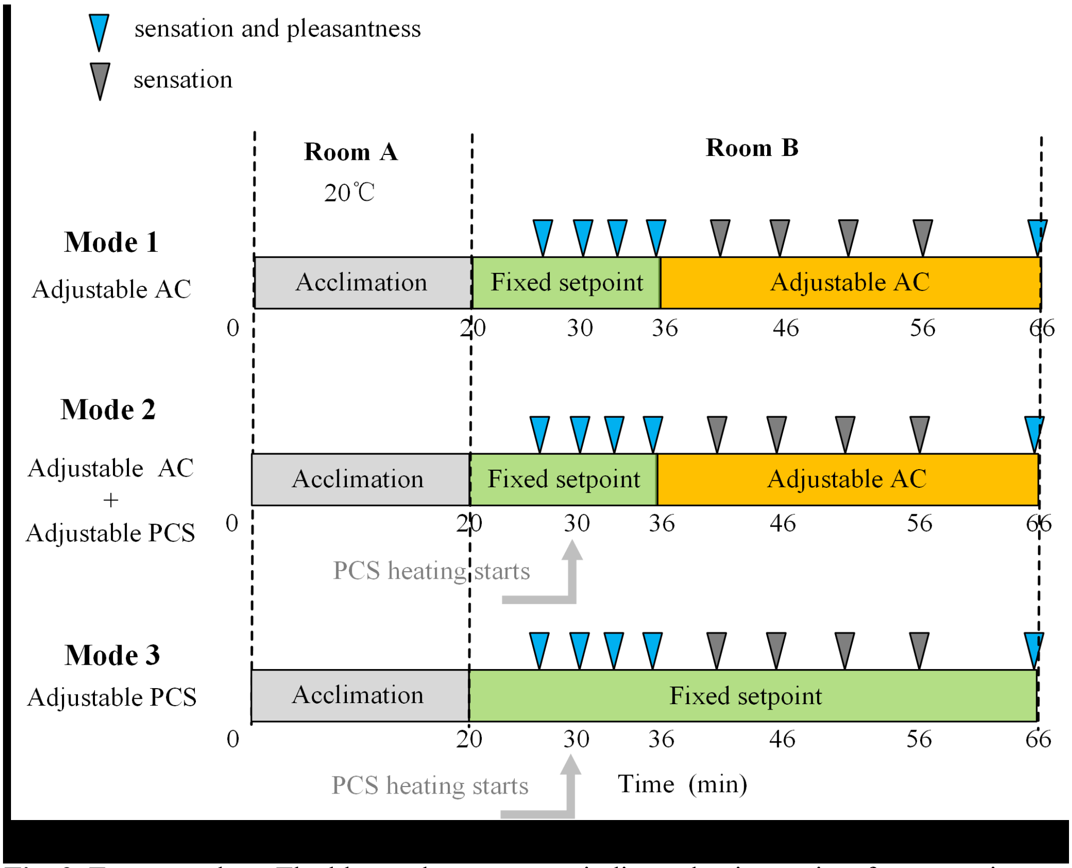

Fig. 3. Test procedure. The blue and grey arrows indicate the time points for answering surveys. At the blue arrows, subjects responded to thermal sensation and pleasantness questions (for the heated local body parts and for the whole-body), while at the grey arrows, subjects answered thermal sensation questions only. At the final arrow, subjects provided sensation for all local body parts (both heated and unheated), and rated pleasantness for the 4 heated body parts.

In Modes 1 and 2, subjects had control over the ambient air temperature but they did not know the AC setpoint temperature. To alter the ambient air temperature, they were prompted to instruct the researcher after the completion of each survey to immediately increase or decrease the temperature an integer amount, e.g., decrease 2°C, or 'no change'. If the subjects requested no change, the researcher would maintain the current indoor temperature until the next survey point. The maximum ambient air temperature change rate under AC-control was roughly 0.25°C/min and varied depending on the magnitude of change requested. In Modes 2 and 3, all five PCS devices were applied simultaneously at the beginning but subjects were allowed to adjust individual power levels. Subjects were requested to keep their left hand continuously on the contact hand warmer so that they experienced the full warming effect. They were allowed to move their right hands to interact with the computer or phone, or they could place it on the PCS for heating (as shown in Fig. 2). The 6 min period of PCS use before AC was designed to encourage occupants to use PCS control before changing the room temperature. The duration (6 minutes) was based on laboratory testing of the time for pleasure sensations to stabilize after local heating [33].

The PCS heating was expected to have no measurable effect on the overall room temperature. The relative humidity for all tests was approximately 50%. All subjects participated in all test conditions but were

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limited to one test per day. Test sessions were held from 9:30-12:00, 14:00-18:00, and 19:00-21:30. The modes and starting temperatures were randomized for each subject.

2.3 Measurement

The study compares the human response to changes in skin temperatures produced by PCSs against those caused by room temperature changes, the main variable controlled by AC. We measured room temperature and humidity using TR-72Ui meters (accuracy ±0.3°C and ±5%) near the center of the room, 1.0 m away from the seated subjects and 0.6 m above the floor. This separation distance was sufficient to isolate the meter from any potential air temperature increases caused by the PCS. The TR-72Ui meters had aluminum foil shields so they were not affected by the radiation from the PCS or other indoor items. Before the formal testing, we also measured the indoor wind velocity near the subjects' seat location. The airflow from AC did not blow onto the subjects, so the air velocity near the workstation was low (below 0.02 m/s). Thus we believe that the airspeed surrounding the subjects represented the typical still air value.

At the outset of each test, the operative temperature is assumed to be equal to room air temperature since each test condition was established at least one hour before the test began. After subjects began controlling the AC, the wall temperatures of the space (masonry) would have lagged behind the changes in air temperature, causing the operative temperature to be somewhat cooler. However, we measured the room air temperature, but not global temperature which is needed to calculate the operative temperature, because the room air temperature reflects the energy use by the AC in practice.

Local skin temperatures at nine body sites were measured every minute using iButton DS1922L devices (accuracy ± 0.5 °C). The neck, hand, and foot were measured as body parts directly heated by the PCS. Measurements from the seat contact area proved unreliable due to locations where the iButtons were placed, which were not in direct contact with the heated cushion. Therefore skin temperatures from the seat area were dropped from the analysis. Temperature measurements of the cheek, upper arm, abdomen, lower back, and thigh were the unheated body sites used to calculate mean skin temperature following the method from [44] given in Equation 1. Only one side of local skin temperatures was measured (left) on the assumption that the human body is bilaterally symmetrical.

$$t_{sk.mean} = 0.07t_{cheek} + 0.19t_{arm} + 0.175t_{abdomen} + 0.175t_{back} + 0.39t_{thigh} \quad (1)$$

Surveys were administered every 3 minutes starting at the 27th minute of the test, three minutes before PCS control was given to subjects. Frequent polling after a change in conditions was needed to capture the dynamic response to the PCS. After the 36th minute, the polling interval was extended to 5 minutes as the dynamic response was expected to diminish with time. The thermal sensation and thermal pleasantness survey scales are shown in Fig. 4. Thermal sensations during the tests might be more extreme than typically found indoors due to the high local heating intensity possible with PCS and the low initial ambient air temperature (down to 14 °C). To account for this, the typical indoor 7-point thermal sensation scale was

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extended adding the extreme categories 'very hot' and 'very cold'. Thermal sensation votes were obtained both for whole-body and for each measured body part. Thermal pleasure was measured on a range from 'very pleasant' to 'neutral' to 'very unpleasant'. Thermal pleasure votes were obtained both for whole-body pleasantness as well as for the four local heated sites (neck, hand, buttocks, and feet). The color scheme for the pleasantness scale reflected the application of heating to correct cool conditions.

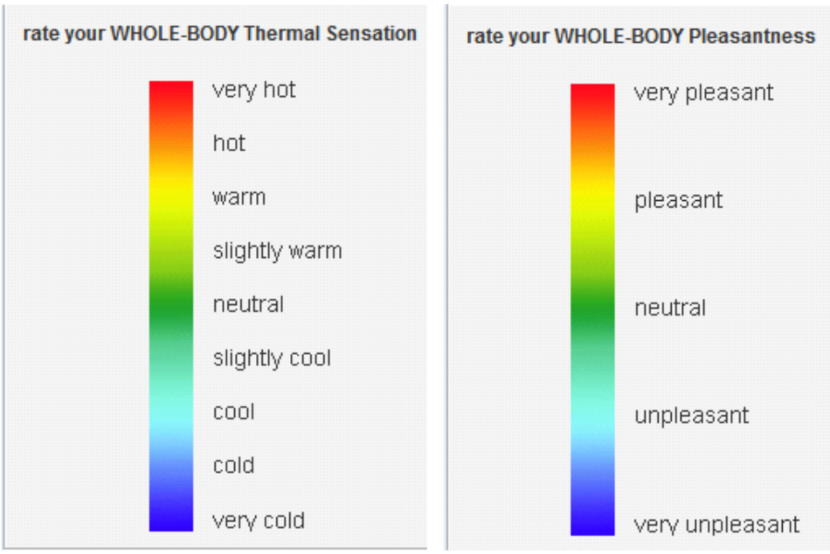

Fig. 4. Scales shown to subjects to rate their thermal sensation and pleasantness.

3. Results

3.1 Physical and physiological responses to AC and PCS warming

Ambient air temperatures and the skin temperatures of body sites that were not directly receiving PCS heating (cheek, arm, abdomen, lower back, and thigh) are shown in Fig. 5. Activating the AC system at the subjects' request after the 36th minute in Modes 1 and 2 increased the indoor temperature. The rate of change in the indoor temperature from the AC is slow, and the final indoor temperature is different for the three starting temperatures. Changes in the skin temperatures of the unheated body parts reflect these changes in air temperature. Air temperature increases in Mode 1 (+4 °C starting from 14 °C , +3 °C starting at 16 °C, and +2 °C starting at 18 °C) led to mean skin temperature increases of 0.9, 0.5, and 0.4 °C respectively. There is little perceptible lag in the timing.

There were smaller temperature changes in Mode 2 compared to Mode 1; air temperature and skin temperature increases in Mode 2 were approximately half those in Mode 1. Subjects in Mode 2 requested less AC heating due to the activation of local skin heating by PCS. The temperatures of unheated sites continued to respond to the indoor temperature, but local site heating from PCS (not presented in this figure) reduced the need for warming indoor room air. Unlike in Mode 1, the room and skin temperatures appear to have reached their final state values at the end of the test (66th minute).

The mean skin temperatures remained almost unchanged when the ambient air temperatures were constant at 14 °C and 16 °C in Mode 3. It is unclear why the mean skin temperature increased 0.3 °C in the

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18 °C condition; we suspect it is due to the lower starting skin temperature at the 20th minute. Finally, Fig. 5 shows that the waste heat from the PCS did not affect the ambient air temperature in a test room of this size.

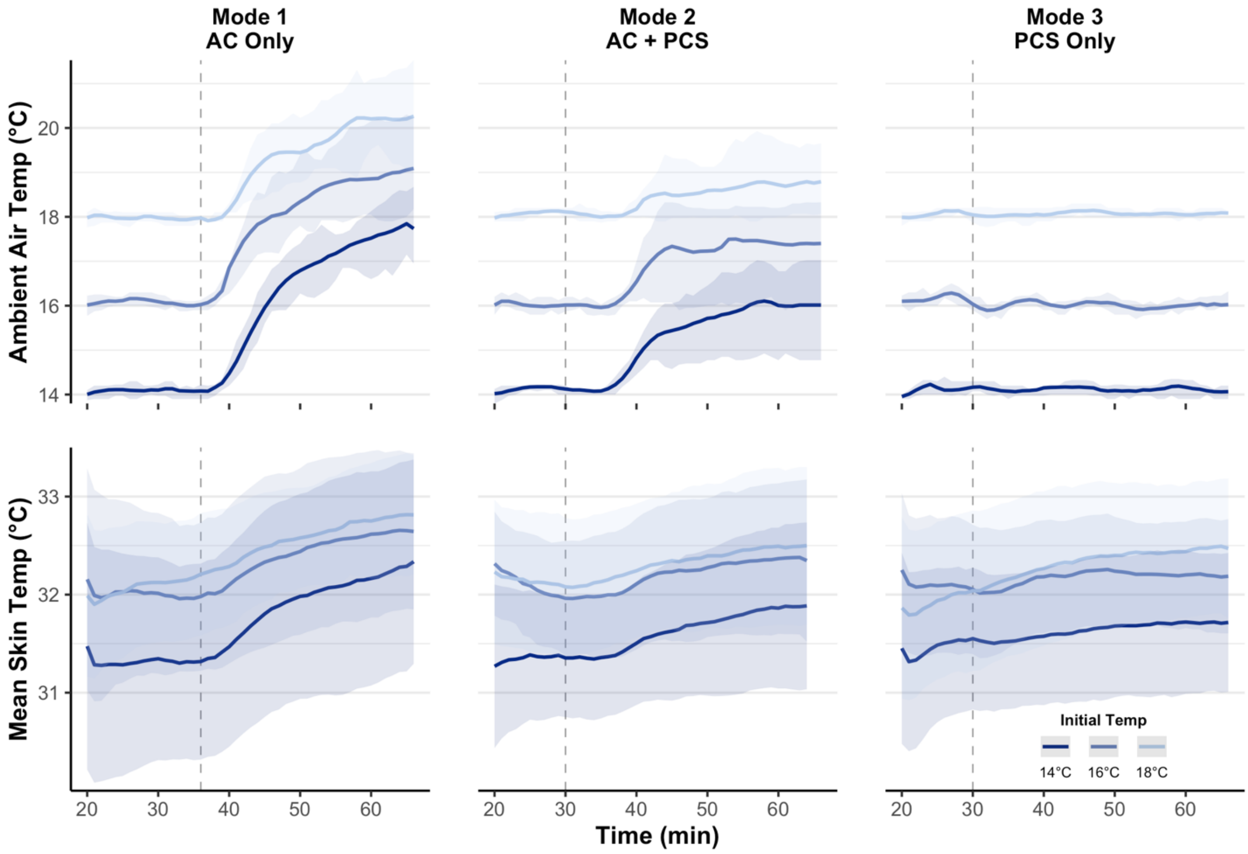

Fig. 5. Time series of ambient air temperatures (top) and mean skin temperatures of the unheated local measurement sites: cheek, arm, abdomen, lower back, and thigh (bottom). Shaded areas show the standard deviations for the group means. AC adjustment starts at the 36th minute; PCS adjustment starts at the 30th minute.

3.2 PCS heating power and local skin temperature

The use of PCS influenced the mean skin temperature of the *heated* local body sites directly. This is similar to the influence of ambient air temperature on the *unheated* body sites reported earlier. Fig. 6 shows the mean skin temperature of the heated body sites (neck, hand, foot) rising 2 to 3.5°C during the test. These are larger increases than the sites warmed only by the ambient air temperature in Modes 1 and 2. Greater increases in local skin temperature occurred at the lowest ambient temperature (14°C); this is noticeable for Mode 3 where PCS was delivering all the heating. However, negligible differences between Mode 2 and Mode 3 highlights the small amount of skin warming provided by the AC compared to the concentrated local PCS heating.

Fig. 6 also shows the electrical power applied to the PCS devices at four locations. In all but the chair, the power was initially strong but reduced by the subjects during the first ten minutes of warm-up. PCS power usage was similar for the 14°C and 16°C indoor starting temperatures, and between 5% and 20% lower for the 18°C starting temperature.

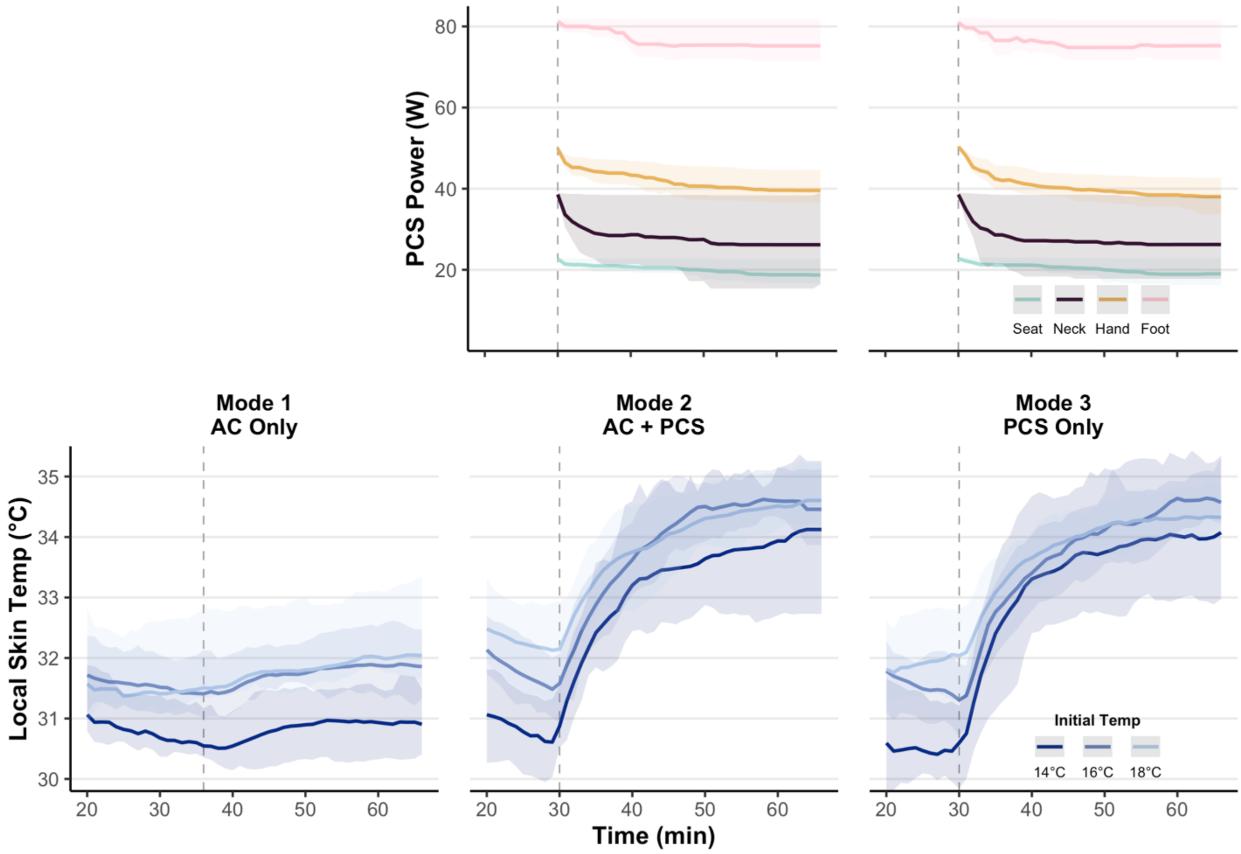

Fig. 6. Electrical power consumed by the four PCS devices (top), and mean skin temperature of the heated sites: neck, hand, and foot (bottom). Power was similar between the different starting temperatures and was therefore averaged.

3.3 Pleasure response to PCS heating

Both the whole-body and local thermal pleasantness votes for the three modes of heating highlight the ability of PCS to elicit pleasure responses. Group means of whole-body pleasantness votes shown in Fig. 7 (top) demonstrate the dramatically different responses to ambient heating (Mode 1 and Mode 2) compared to local heating using PCS (Mode 2 and Mode 3). Comparison of Mode 1 and Mode 2 shows both muted and slowed pleasure response from using AC to increase the ambient air temperature, compared to directly heating the body using PCS. The room air warming in Mode 1 (see Fig. 5) produced small positive pleasure increases, with the final rating slightly above 'neutral' for 16 °C and 18 °C starting temperatures, and at 'neutral' for 14 °C starting temperature. Despite increasing air temperatures at the end of the tests, trends in pleasantness do not show final votes much above neutral. There was a negligible difference in the group pleasure response between Mode 2 and Mode 3, and the effect of the initial starting temperature was small. Pleasure from immediate warming by the PCS appears to overpower any pleasure contribution from the change in ambient air temperatures. The 14 °C test condition required more time but reached an equal level of pleasure as the other two starting temperatures in both Modes 2 and 3.

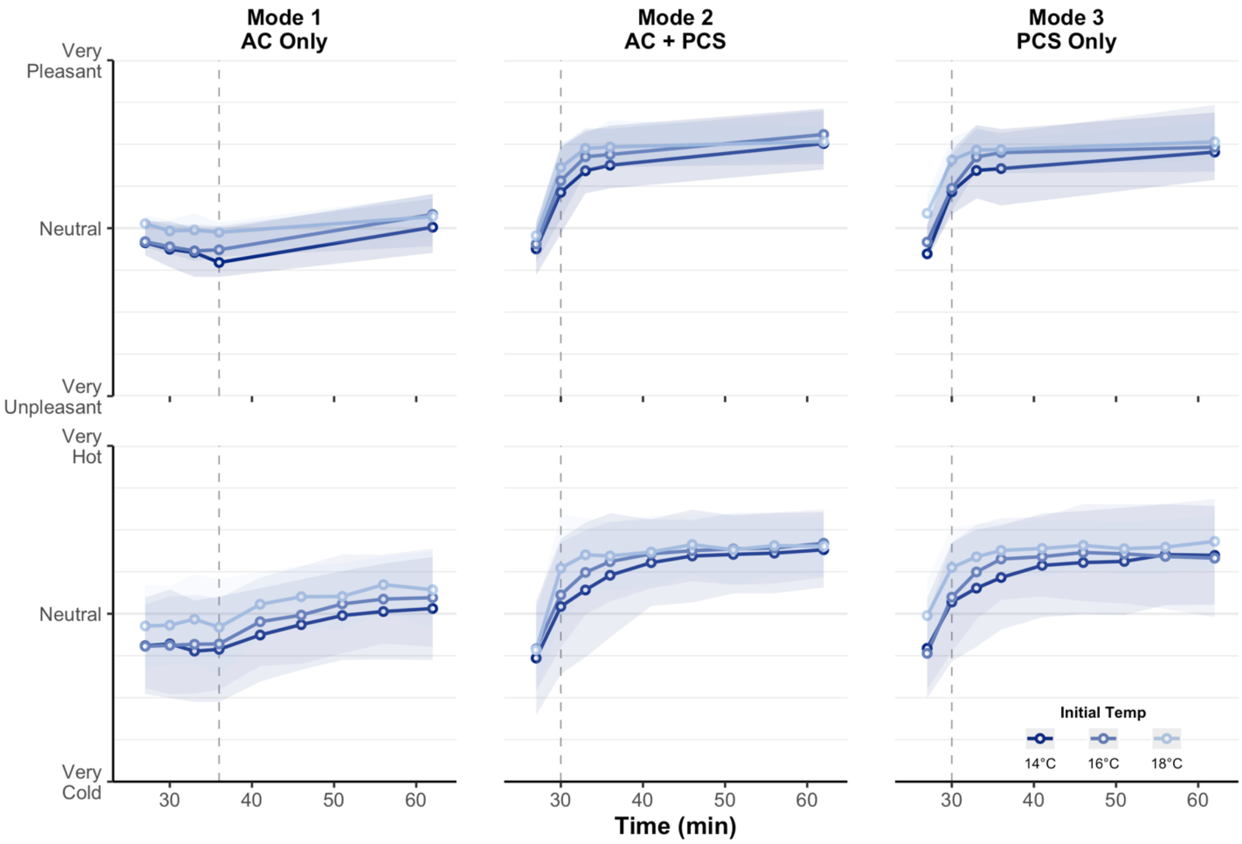

Fig. 7. Group mean of whole-body thermal pleasantness votes (top) and thermal sensation (bottom). Time series are shown for the three modes tested. Line colors show the initial zone temperature. Dashed lines indicate the point where subjects could modify their environment. Shaded areas show ±1 standard deviation**.**

3.4 Thermal sensation

The pleasantness votes in Fig. 7 (top) are compared to the simultaneous thermal sensation votes in Fig. 7 (bottom). AC warming in Mode 1 slowly changed subjects' sensation from the cool side of neutral to the warm side of neutral. Notably, sensation votes never reached 'slightly warm' in any of the three starting temperatures. In contrast, PCS heating in Modes 2 and 3 led to a change from 'neutral' to between 'slightly warm' and 'warm' within 5 minutes. The intensity of sensation change is greatest at the beginning and tapers off throughout the test.

Fig. 8 shows that occupants' thermal sensation was approximately equal for both the heated and unheated body sites. This was true for AC (Mode 1) as well as PCS heating (Modes 2 and 3). We had not anticipated that thermal sensation at unheated body sites would equal that at PCS-heated sites. The actual skin temperatures of unheated sites changed very little with the heating of separate sites by PCS (see Fig. 5). The fact that whole-body thermal sensations closely tracked the sensation of the heated sites suggests that the most pleasant or corrective skin temperature changes transform the perception of other body sites.

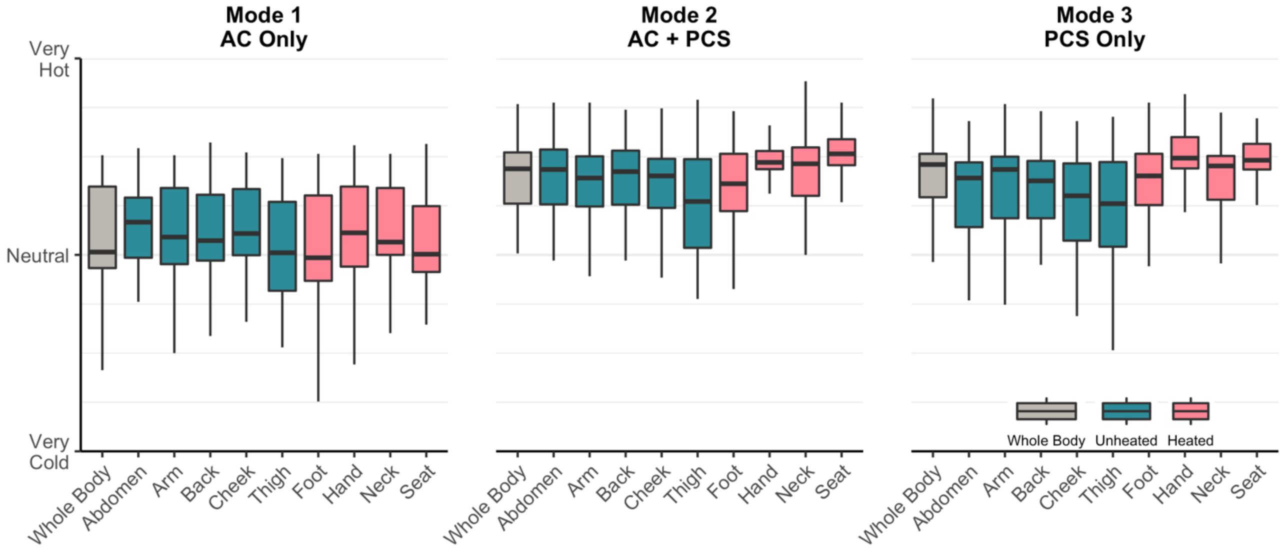

Fig. 8. Thermal sensation votes for heated and unheated body sites at the conclusion of the test (the 66th minute).

3.5 Local and whole-body pleasure

The large influence of PCS on whole-body pleasure and sensation in Mode 2 and 3 led us to wonder if the same influence is observed in local pleasure at the site of PCS warming. Fig. 9 compares whole-body and local pleasantness votes for each warmed body site. In all cases, local pleasure is very close to whole-body pleasure (see the correlation matrices of local and overall pleasantness votes in Fig. 9). However, small differences between local and whole-body pleasure are consistent throughout the exposures. The slightly higher thermal pleasure was experienced at the seat and neck sites compared to the whole-body pleasure, while pleasure at the foot was lower compared to the other sites. The whole-body pleasure is coincident with the *lowest* local pleasure among the four heated body parts (e.g. foot). As with the whole-body pleasantness votes in Fig. 7, the local votes from Mode 2 and Mode 3 are basically identical. Finally, the pleasantness votes in Fig. 9 parallel the changes in local heated skin temperature presented in Fig. 6. This suggests a relationship between the corrective capacity of the PCS device, the associated change in skin temperatures, and the resulting thermal pleasure.

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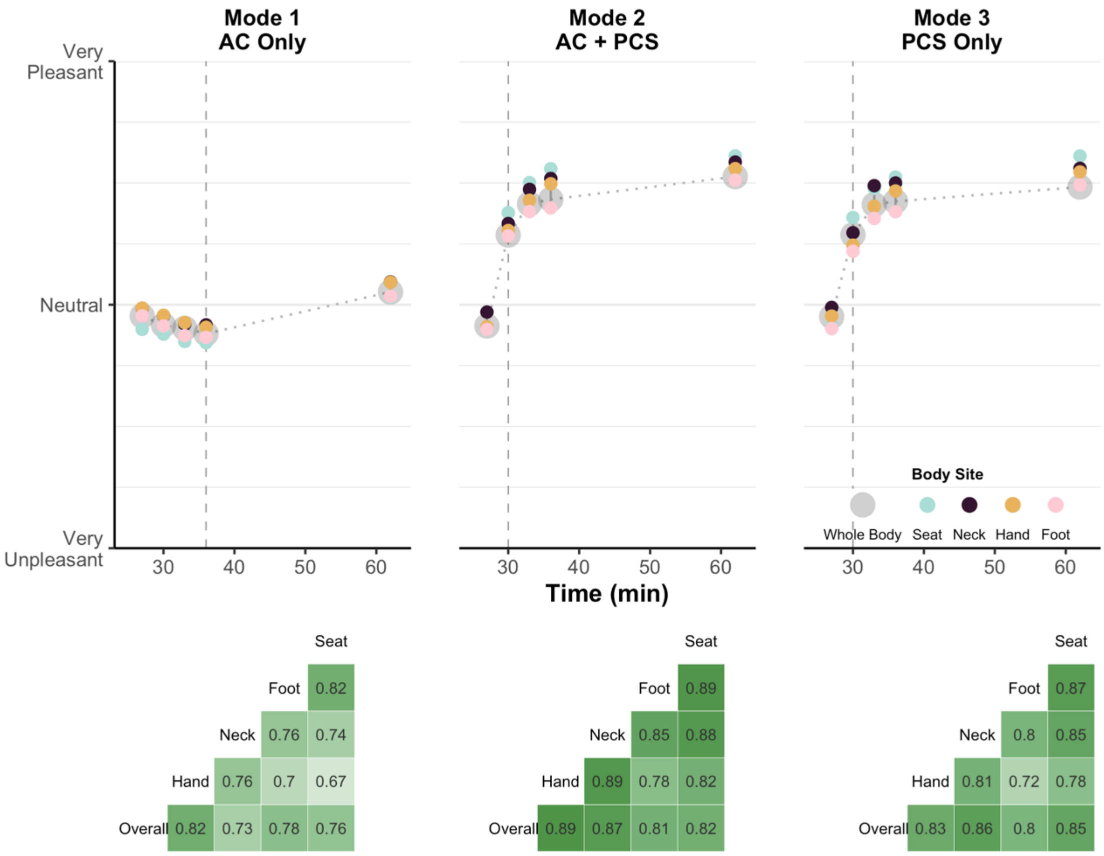

Fig. 9. Group mean of whole-body thermal pleasantness votes (large grey points and dotted grey line) with simultaneous local pleasantness votes of the four warmed body sites (small colored points). Time series are shown for the three modes tested. Pleasantness votes are averaged across the three starting temperatures (14°C, 16°C, and 18°C). Dashed lines indicate the point where subjects could first modify their environment. Correlation matrices are shown below each plot and report the Spearman's rank correlation coefficient between different skin temperatures.

3.6 Effects of spatial and temporal alliesthesia

The spatial alliesthesia hypothesis posits that thermal pleasure arises from local skin temperatures that contrast with a non-neutral whole-body condition. Fig. 5 and 6 show negligible changes in skin temperature of unheated body sites in Modes 2 and 3 but changes from 2 ºC to 3.5 ºC at the four PCS-heated body sites. These changes produce temperature gradients between body parts requisite for spatial alliesthesia. Fig. 10 compares the change in thermal pleasantness votes with the change in local skin temperatures. Most of the change in skin temperature and thermal pleasure occurs in the first three or four minutes of PCS heating in Modes 2 and 3. Slower skin temperature changes later in the test (Fig. 6, minutes 33 to 66) suggest that differences between heated and unheated sites were steady-state. Yet there was no diminution in the high pleasure level during this phase. The similarity in pleasure votes between Modes 2 and Mode 3 again shows that the rapid local heating from PCS is more influential in driving pleasure responses than the slower changes in ambient air temperature from AC.

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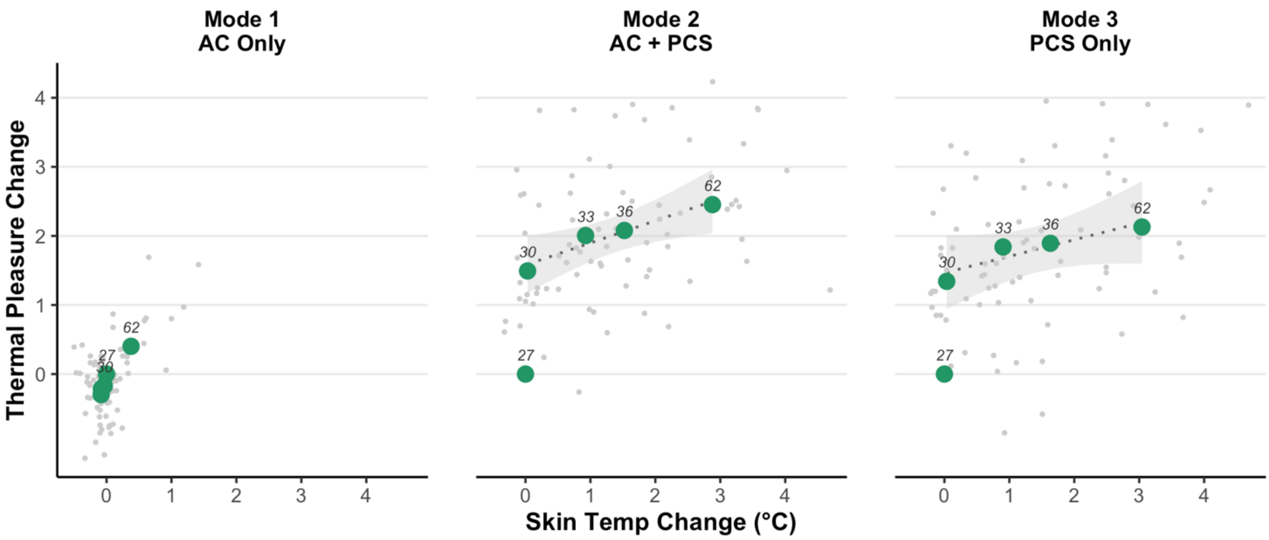

Fig. 10. The mean change in overall pleasure vote corresponding with the mean change in skin temperature across the four heated body sites. The three initial starting temperatures are collapsed into one group. Linear regressions are shown for Mode 3 and Mode 2 with the confidence interval as a shaded grey area. Light grey dots show data for individual subjects. The time of the pleasure responses is superimposed for reference, in minutes from the start of acclimatization.

4. Discussion

4.1 Corrective capacity of PCS heaters

The ambient air and PCS temperature changes in Mode 2 led to an approximately 0.2 ºC increase in skin temperature at unheated body sites (Fig. 5) and a 2 to 3.5 ºC increase at heated body sites (Fig. 6). The same procedure for the PCS-only test (Mode 3) had similar effects on skin temperatures using much less total energy. This demonstrates the efficacy of PCS in heating occupants across a wide range of cool indoor air temperatures. The skin temperatures and pleasantness in Mode 3 with initial temperatures of 16 and 18 ºC (Fig. 6 and 7) appear almost interchangeable. However, the drop in mean heated skin temperature and pleasantness becomes significant at 14 ºC and the heated skin temperatures did not stabilize during the test. This suggests that for this combination of PCS devices, 14 ºC may be approaching a practical limit below which indoor room temperature must be raised.

We calculated the corrective power of the PCS devices used in our study with a variant of the method from [1]. Assuming 20 °C as the indoor neutral temperature for the subjects' clothing and activity levels based on the PMV model, Fig. 7 shows that even under 14°C ambient air temperature, thermal sensation was warmer than neutral. The CP of this experimental PCS suite is therefore higher than 6 K. AC power consumption of test Room B was measured in an earlier study [36]; average AC power usage at setpoints of 14, 16, and 18°C is 837, 1267, and 1683 W respectively. Each 1 °C decrease in the setpoint temperature reduces the AC power of the room by about 200 W (12% using 1683 W as the base case). In Fig. 5, the energy efficiency can be estimated according to the final indoor temperatures under the three modes. Specifically, compared to the conditions with adjustable AC only, adjustable AC and PCS (Mode 2) is 1.5-2 °C lower, and PCS only (Mode 3) is 2-4 °C lower. The AC power was thus reduced by 300-400 and 400-800 W, respectively. Meanwhile, the average heating power of the PCS suite in this study is 160-170 W. The

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lower power requirements of PCS compare to AC demonstrates the potential energy savings of PCS.

4.2 Whole body and local pleasure

The local pleasure votes were nearly identical to the whole-body pleasure votes (Fig. 9) in all modes. This finding suggests that future studies of spatial alliesthesia may not need to evaluate them as distinct phenomena. The small differences that did occur between local- and whole-body pleasure votes were very consistent across body sites. The seat and neck were slightly higher while the feet were slightly lower. The whole-body pleasantness is virtually identical to the lowest local pleasantness vote. The unheated body parts did not appear to affect the whole-body pleasure responses. This result is consistent with the 'complaint model' of comfort [32] in which the least comfortable body part is the primary driver of whole-body comfort and the influence of the more comfortable parts is limited.

There remain open questions within the alliesthesia thermal perception framework about how temporal changes in skin temperature and spatial differences in skin temperature (among body sites) might interact. In this study, skin temperature change occurs in all three tested modes at each initial temperature. Muted pleasure responses in Mode 1 highlight that 1) rate of change in skin temperature from AC is too slow to produce alliesthesia, and 2) conventional AC systems produce no local temperature differences across body sites. In contrast, PCS in modes 2 and 3 generated fast skin temperature changes within the first five minutes that correlate with large pleasure increases (Fig 10). This reflects the temporal component of alliesthesia, where fast corrective changes elicit a pleasure response. Towards the end of the exposures, skin temperatures were relatively stable but pleasure votes remained positive. This is the spatial component of alliesthesia, driven by the differences between heated and unheated body sites. Both temporal and spatial alliesthesia occurred, with the former dominating the initial PCS heating and the latter dominating the remaining period. Similar onset and tail phases were reported by [19].

The pleasantness votes had similar magnitudes for both temporal and spatial alliesthesia components (see Fig. 9). This is of interest to future research efforts as it suggests the neural mechanisms of temporal and spatial alliesthesia may be fundamentally different. Temporal alliesthesia likely reflects the pronounced sensitivity of cutaneous thermoreceptors to rates of change [45]. In contrast, spatial alliesthesia is based on steady-state temperature differences between separated body sites and must therefore originate further along with the central nervous system. Because the heightened rate of thermoreceptor activity from rapid changes in skin temperature does not occur under spatial alliesthesia, there may be an additional mechanism of neural integration that is responsible for generating pleasure. Whatever the mechanism, it provides the same level of pleasure as the temporal component of alliesthesia.

4.3 Heating systems of the future

HVAC systems are currently designed to create uniform and neutral indoor environments for occupants. Systems are purposefully designed to minimize local discomfort caused by draft, vertical temperature difference, asymmetric radiation, and too-warm or too-cool surfaces [5]. Such conditions are unlikely to provide the types of local skin temperature differences or transients required for producing thermal pleasure; this is evident in the modest pleasure experienced in Mode 1 (Figs. 7-10). There are two primary reasons for this: 1) AC inherently requires time to warm a room-sized space, and 2) skin temperature changes produced by uniform convective and radiant heating systems are slow. In contrast, PCS is able to more intensely and efficiently channel heating energy into the occupant, making rapid local skin temperature change possible. In addition, control over the PCS heating power ensures that every individual can tailor the microclimate to suit their temperature preferences. PCS is therefore inherently better at generating thermal pleasure compared to traditional AC, whether working in conjunction with (Mode 2) or independent of (Mode 3) the centralized system.

4.4 Limitations

The purpose of this study was to investigate the potential of adjustable PCS heaters to produce thermal pleasantness in cool environments compared with a traditional AC system that is under personal occupant control. While the results suggest that PCS are inherently better at eliciting alliesthesia responses, there are some limitations to our study that should be considered before efforts to operationalize PCS in buildings are realized:

(1) The study design used five PCS simultaneously. The predicted whole-body pleasantness might be different if only one or two local body parts are heated; we plan to address this issue in a report on a separate study.

(2) It is unclear how much skin surface area should be heated to elicit pleasure. We believe it will vary by body parts such that the concept of area summation [46] would inform the design of PCS. For example, the 6.25 cm^2 wearable device on the wrist in [47] improved local pleasantness but the effect on the whole-body pleasantness was 2-3 times smaller. Future research efforts should explore the use of small and discrete heating elements at different body sites.

(3) We tested generic PCS that target conventional heating sites. Optimizing heating effectiveness will depend on sensitives (as discussed) as well as device parameters affecting heat transfer efficiency (e.g. system capacity, transfer losses, target surface area and thermophysiological attributes). Effectiveness might also depend on physiological effects, such as applying heat directly to vasoconstricted areas to reduce the local physical discomfort caused by cooling from vasoconstriction. Such effects may have been occurring in these tests but vasoconstriction was not measured.

5. Conclusions

This study compared the potential of generic PCS heaters and a room AC heating system at eliciting thermal pleasantness for occupants exposed to three cool ambient air temperatures. The two systems were tested independently and at the same time, in each case under the control of the occupant. Skin temperatures, thermal sensation and pleasantness votes were measured at heated and unheated body sites. The main conclusions are:

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(1) Whole-body thermal pleasantness closely followed the pleasantness of the heated local body sites. Skin temperatures of the larger areas of unheated skin seemed to have no influence on the pleasure experience from PCS.
(2) The role of ambient air temperature was much reduced with effective PCS heating. Thermal pleasantness and sensations were similar across the initial ambient air temperatures (14, 16, and 18°C). PCS can therefore provide thermal satisfaction across a wide range of ambient air temperatures well below traditional heating setpoints of HVAC systems.
(3) PCS first triggers temporal alliesthesia from rapid increases in local skin temperatures and then spatial alliesthesia by maintaining one or more warmed local body sites to counter the cool mean skin temperature. Equivalent levels of pleasantness were observed for both components of alliesthesia over the course of the tests. Future research should build up existing work exploring the neural bases of temporal alliesthesia [20] and expand it to cover spatial alliesthesia.
(4) Conventional AC systems are unlikely to generate thermal pleasure from heating due to the time it takes to heat an entire room. In addition, room-scale systems produce uniform conditions around the occupant that cannot provide the substantial benefits from spatial alliesthesia reported in this study. In contrast. PCS create fast and intense heating that is non-uniformly distributed across the body. These temporal and spatial characteristics give PCS a significant advantage in generating thermal pleasure.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Edward Arens involved in conceptualization (equal); writing-review and editing (lead); resources (supporting).

John Elson involved in conceptualization (supporting); funding acquisition (supporting); writing-review and editing (supporting).

Yingdong He involved in investigation (lead); formal analysis (equal); visualization (equal); writing-original draft (lead); writing-review and editing (supporting).

Nianping Li involved in funding acquisition (equal); investigation (equal); resources (supporting).

Clay Maranville involved in funding acquisition (supporting); writing-review and editing (supporting).

Thomas Parkinson involved in funding acquisition (supporting); formal analysis (equal); resources (supporting); visualization (lead); writing-review and editing (equal).

Jinqing Peng involved in funding acquisition (equal); investigation (equal); resources (supporting).

Hui Zhang involved in conceptualization (equal); writing-review and editing (equal); resources (supporting).

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