Title
Thermal comfort evaluated for combinations of energy-efficient personal heating and cooling devices

Authors
Luo, Maohui
Arens, Edward
Zhang, Hui
et al.

Publication Date
2018-10-01

DOI
10.1016/j.buildenv.2018.07.008

Thermal comfort evaluated for combinations of energy-efficient personal heating and cooling devices

Maohui Luo[1], Edward Arens[1*], Hui Zhang[1], Ali Ghahramani[1], Zhe Wang[1]

[1] Center for the Built Environment, University of California, Berkeley, U.S.

[*]*Corresponding email: earens@berkeley.edu*

Personal comfort systems (PCS) have potential to fulfill building occupants' personal thermal comfort preferences with great efficiency. But to integrate them into building conditioning, there must be a broader selection of PCS devices available. Design guidance and standards are needed to assure that such devices provide high levels of comfort effectiveness and energy efficiency. This study addresses these needs. A suite of minimum-power PCS devices was built that target body parts significant to alliesthesia—a heated shoe insole, heated/cooled wristpad, small deskfan, and heated/cooled chair. They were tested in a climate chamber under cool and warm conditions using both thermal-manikin and human-subjects. Their efficiency at physically heating/cooling the body is high; the combined suite has a coefficient of performance (COP) of 3.6 for cooling and 0.88 for heating. The subjects' whole body thermal acceptance and thermal comfort perception were improved by the devices in an additive manner; using the combined suite over 80% of people accepted ambient temperatures of 18°C and 29°C. The PCS 'corrects' the ambient temperature towards thermal neutrality by as much as 6.5K cooling and 3.6K heating, overcoming building occupants' typical interpersonal thermal differences and making possible large HVAC energy savings in buildings. The idea of temperature corrective power can be the basis of standards for PCS.

KEYWORDS

Thermal comfort; building energy saving; personal comfort system (PCS); local heating/cooling; heated and cooled chair; corrective power (CP)

NOMENCLATURE

BMI	body mass index
CBE	center for built environment
COP	coefficient of performance

CP	corrective power
EHT	equivalent homogenous temperature
HVAC	heating, ventilating and air conditioning
PCS	personal comfort system
PMV	predicted mean vote
TSV	thermal sensation vote
TCV	thermal comfort vote
C	chair
F	fan
I	insole
W	wrist-pad
RH	relative humidity (%)
T_{sk}	skin surface temperature (^{o}C)
A	surface area (m^2)
Q	heat loss (W/m^2)
I_{clo}	clothing insulation (clo, 1 clo = $55w/m^2$)

1 INTRODUCTION

The energy expenditure for air conditioning (HVAC) is increasing rapidly across the globe, approaching 20% of total national consumption in large economic entities such as United States [1], Europe [2], and China [3]. Most of this is consumed in the effort to minimize thermal discomfort, which nonetheless continues to affect at least 20% of commercial building occupants. This unfortunate situation may be the best that current technology and practice can accomplish. It is essential to explore energy-efficient alternatives that assure a better comfort outcome.

1.1 Thermal comfort in buildings

It is common in modern buildings to deliver indoor thermal environments with a narrow range of temperature and humidity that is constant over time, uniform throughout space, and

targeting the occupants' perceptual thermal neutrality. This has two undesirable consequences. First, achieving narrowness, constancy, and uniformity of thermal conditions in a space requires far more energy than looser forms of control [4][5]. Second, because groups of occupants contain individuals with widely varying thermal neutralities and comfort requirements, even the most optimized group neutrality will leave a substantial proportion of the group (~20%) either too warm or too cold [6]. Therefore, the best performance for this type of control is quite limited [7].

In contrast to this are two general approaches: 1) personal control over the ambient space temperature, as provided by thermostats in private offices, and 2) localized thermal conditioning of occupants' bodies, as done by personal comfort systems (PCS). The latter has been found capable of providing 100% occupant thermal comfort in spaces where substantial numbers of people occupy each temperature control zone [8]. Local thermal conditioning also promises to lower the energy consumed by central HVAC (unlike the private office approach) because it is inherently more efficient to heat and cool the individual occupants directly than to condition the entire ambient space [9].

Local thermal conditioning devices can take advantage of the *alliesthesia* they induce in people, a sensation of pleasantness that occurs with the relief of physiological thermal stressors [10]. Alliesthesia may be categorized into two subsets. First, 'temporal alliesthesia' occurs during transients in the body's thermal state from non-neutral toward neutrality, in which sensory input is perceived more strongly than in static states [10, 11,12]. Local conditioning devices typically have rapid response times, making them capable of activating this form of alliesthesia in occupants whose thermal conditions or activity levels vary during the course of the day. Second, 'spatial alliesthesia' refers to effects of non-neutral thermal conditions occurring on various body parts at the same time [13,14,15]. It is possible to target a small amount of energy on the most sensitive body part(s) to achieve a strong whole-body comfort effect. Spatially non-uniform thermal comfort was first documented in Zhang [16], in which individual portions of the body were isolated and heated/cooled while the surrounding environment was kept independently warm, cool or neutral. The extremities (hands, feet, face, neck) temperatures were observed to be very important to the perception of whole-body thermal comfort. Discomfort from a cold foot/hand for example would dictate whole-body discomfort, so by concentrating warming on the foot and hand, whole-body comfort can be efficiently maintained in cool environments. Similarly, cooling the head and back/seat are critical for comfort in warm environments [17][18]. These psychophysiological principles will

underlie the most effective and efficient PCS designs.

1.2 Personal comfort systems (PCS)

Systems and devices that heat or cool individual occupants (or small groups of occupants) have existed for many years. Various forms of desk, wall, and ceiling fans, radiant or convective heaters, and temperature-controlled surfaces on chairs, desks, and floors, have been available in the marketplace. They are mostly used as correctives by individuals whose thermal requirements are warmer or cooler than that of the average population. Their use has rarely been thought of as integral to the building's conditioning system. An example of this are room fans; although their cooling efficiency per occupant is higher than that of HVAC cooling, they have rarely been interfaced with the HVAC thermostatic control. Since fans cool occupants individually or in small groups, with spatial coverage that is inherently non-uniform, the engineer's design concern about how to assure that there is full coverage (or availability) to occupants is a legitimate one that has not yet been seriously addressed.

On the heating side, the personal device efficiency is key. Occupants have also long used convective/radiant heaters to help compensate for interpersonal thermal differences. These heaters have in most cases been highly inefficient, requiring wattages on a per capita basis similar to that of the HVAC system (500-1500W). Their high power creates thermal loads that disrupt the control of the HVAC system, so they are often banned by building managers. For this reason, individual heaters must operate far more efficiently to be designated as PCS. Designing local heaters to high thermal efficiency is an important priority. Deciding the practical limits for PCS designation may require more experience with what is possible in efficient heater design.

A range of commercial and prototype PCS devices have already been investigated in laboratory and field studies. A literature review by Vesely and Zeiler [19] found that personalized heating/cooling devices maintaining thermal comfort at ambient temperatures 4–5K higher or lower than those recommended in current standards. A detailed literature review by Zhang et al. [13] summarizes the state of PCS development and evaluates their comfort-correcting 'corrective power (CP)'. Studies of additional PCS devices have been published since then, e.g., Luo et al. [20], Shahzad et al. [21], Vesely et al. [22], and He et al. [23]. But to date, not many PCS have been manufactured and evaluated. Among the impediments to creating a market for PCS is the lack of standardized performance specifications or methods for testing PCS performance. Also, a clear view of how to integrate them into HVAC has not been established.

1.3 The objectives of this study

The study was designed to establish the comfort and energy effects of a suite of highly efficient PCS devices, individually and in their combinations. Their heat transfer performance versus their power input would be systematically determined by thermal manikin measurements. Human comfort improvement would be assessed with physiological and subjective measurements, looking also into the pattern of responses from groups of occupants whose comfort requirements vary under heating and cooling conditions. This information would permit the energy-saving potential of the devices, and their future role in building HVAC control, to be simulated. Together, this work is intended to inform both future PCS designs and new standard methods for evaluating PCS performance, and to support the integration of PCS into the design and operation of HVAC and buildings.

2 METHODS

2.1 Development of PCS devices

(a) The *heated/cooled chair* (Figure 1.a) has been under development for several years [24] [25] [26]. It is battery-powered, with seat and back separately controlled to four levels of heating or cooling. The total maximum input power is 14W for heating and 3.6W for cooling. The chair design is based on the observation that heating and cooling the human torso is effective—the torso is especially sensitive to its skin temperature change, even though its range of temperature variation is normally small [16][27].

(b) The *heated/cooled wristpad* (Figure 1.b) provides heating and cooling to the wrists, hands, and fingers. The maximum input power is 7W for heating and 2.4W for cooling. The heating function of the wristpad is designed to counter the large variation in hand temperature normally caused by vasoconstriction, which also causes local discomfort and loss of dexterity. In cooling mode, extensive blood circulation below the inner wrist surface allows a high rate of heat extraction from the hand and arm. As with the chair, the heating is provided by conduction from resistive strips, supplemented by radiant insulation, and the cooling is provided by convective cooling of the fabric layer supporting the wrist.

(c) The *heated insole* (Figure 1.c) was similarly designed to offset vasoconstriction-caused cooling of the feet, a major source of discomfort both locally and whole-body. The maximum input battery power for both insoles together is 2.4W, delivered via discrete conductive elements in the insole upper surface. The insole is wirelessly charged and is based on the

observation that foot warming is critical for whole-body thermal comfort in cold conditions [16][18].

(d) The small *deskfan* (Figure 1.d), based on a USB-powered fan with <2W power input, cools the face and upper body under warm conditions. A warm face and breathing zone is perceived as uncomfortable in neutral and warm ambient conditions, and a small area of air movement in the head/neck region has an outsized effect on thermal comfort [28][29]. There are two other related effects that may encourage the adoption of these devices. The deskfan appears to have a very significant effect in reducing the concentration of respired CO_2 that accumulates in a person's breathing zone, thereby possibly improving their productivity. It also improves the perception of air quality [30].

(e) The *overall system* (Figure 1.e). In addition to the PCS prototypes shown in a, b, c, d, Figure 1.e gives an overall picture of these devices and demonstrates how they work in an office workstation scenario. In this project, each of the four devices was eventually equipped to be wirelessly powered, using magnetic resonance coupling from transmitters either under the desktop or in a floor mat. However, in the tests reported here the wireless transmission was not yet activated and the devices were powered either by a low-voltage direct current supply cable or battery.

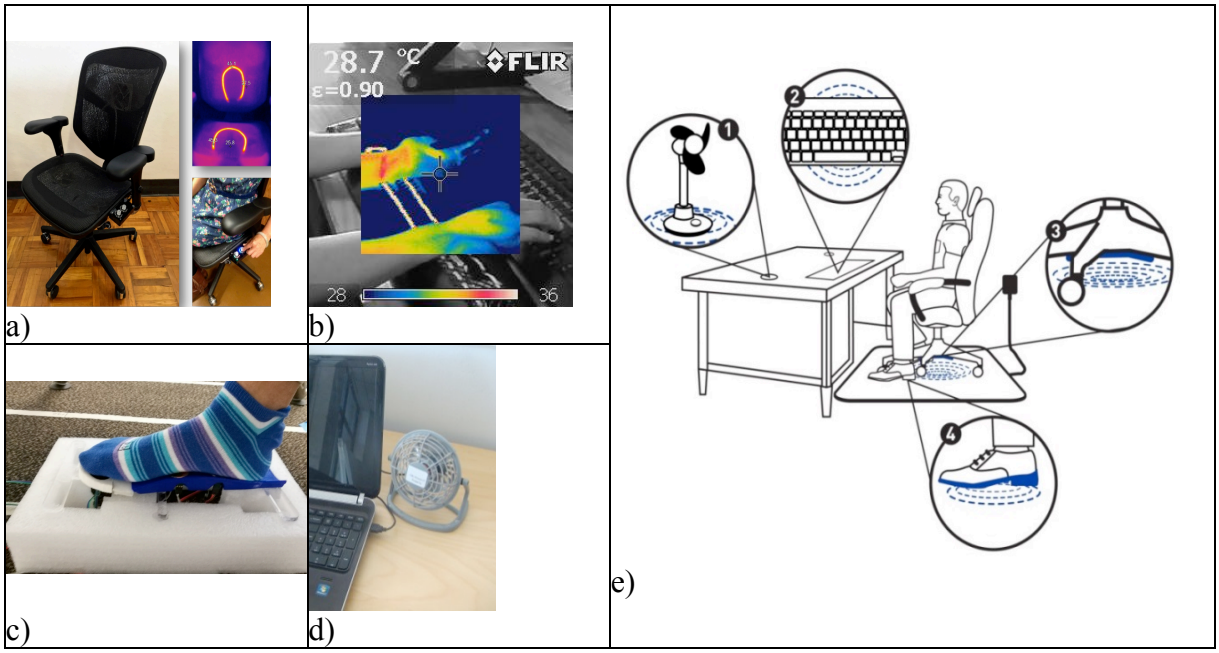


Figure 1. Images of the PCS devices, a) heating/cooling chair, b) heating/cooling wristpad, c) heating insole, d) cooling deskfan, e) overall PCS system. (The overall figure was made by Witricity company)

2.2 Determining PCS-to-human heat transfer using a thermal manikin

The localized heating/cooling provided by PCS devices can be characterized by *equivalent homogenous temperature* (EHT) [31] [32]. EHT quantifies local human body heat loss in any non-uniform condition by comparing it against exposure to an equivalent homogenous, still-air ambient environment. A higher EHT represents a warmer ambient environment.

Thermal manikins are used to quantify EHT. For PCS, segmented manikins are required. The CBE manikin has 16 individual segments (j) with defined surface areas A_j (m^2) [33]. The skin surface temperature of each segment $T_{sk,j}$ (kelvin units) is controlled and the rate of heat loss Q_j (W) recorded. For each specific body segment, EHT_j is calculated by Equation (1.1a). I_j represents clothing insulation (clo) of the body segment in a reference condition; 0.155 is the ratio for converting the insulation unit 'clo' to 'W/m^2'.

$$EHT_j = T_{sk,j} - \frac{Q_j}{A_j} \times I_j \times 0.155 \qquad \text{(K)} \tag{1.1a}$$

Whole-body EHT is calculated by Equation (1.1b), in which Q, A, and I represent the whole-body heat loss (W), surface area (m^2), and clothing insulation (clo) respectively.

$$EHT_{whole-body} = T_{sk,j} - \frac{Q}{A} \times I \times 0.155 \tag{1.1b}$$

Published EHT results from thermal manikin tests of PCS devices have been converted into corrective power [13]. The *CP* values quantify the ability of the PCS devices to correct ambient temperature towards a person's thermal neutrality. Equation 1.2 defines CP_j for each body part in K units, derived from EHT_j differences between PCS and no-PCS (EHT_j - $EHT_{j\_reference}$). For the overall CP value, we can replace the local body parts' EHT_j with whole-body $EHT_{whole\text{-}body}$.

$$CP_{EHT_j} = EHT_j - EHT_{j\_reference} \tag{1.2}$$

CP may also be expressed in watt units, expressing the difference in body heat loss between being exposed to PCS and being in the same ambient condition without PCS. The watt differences are directly measured by the thermal manikin in sequential tests (Q_i - $Q_{reference}$; Equation 1.3a). As with *EHT*, whole-body heat loss *CP* can be calculated by replacing local heat loss Q_j with overall heat loss Q.

$$CP_{Q_j} = A_j \times \left(Q_j - Q_{j\_reference}\right) \qquad \text{(W)} \tag{1.3}$$

From this, a device-level 'coefficient of performance' (*COP*) may be defined to represent the energy efficiency of PCS devices.

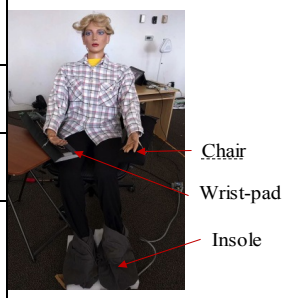
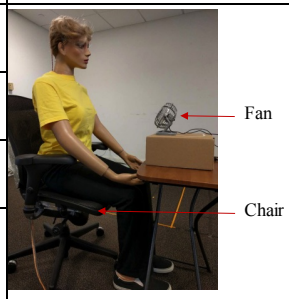
$$COP = \frac{CP_Q}{Power\ input} \tag{1.4}$$

Testing: Table 1 shows the thermal manikin test conditions and corresponding test setups. In the heating scenario, chair heating, insole heating, wristpad heating and the combination of the three were tested in the cool ambient condition of 18°C, 40%RH. The clothing represented normal wintertime office wear: T-shirt, long-sleeve shirt, long pants, and socks. Its insulation was 0.65 Clo, including the thermal resistance provided by the chair.

In the cooling scenario, chair cooling, wristpad cooling, deskfan cooling, and the combination of the three, were tested in the warm ambient condition of 29°C, 40%RH. The clothing represented normal summer casual office wear: short-sleeved T-shirt, long pants, and socks, with 0.5 Clo insulation including chair. In all the test conditions, the skin surface temperature T_{sk} of all manikin segments was uniformly maintained at 34°C to represent a balanced state of comfort across the body.

Although the manikin has less than half the weight of a person, the contact area in the heated/cooled portion of this chair seat and the wristpad was indistinguishable between the two weights, so no weight adjustments were made to the manikin.

Table 1. Thermal manikin test

Heating scenarios (18°C, 40% RH)	Test scene	Cooling scenarios (29°C, 40% RH)	Test scene
Chair heating		Chair cooling	
Insole heating		Insole cooling	
Wristpad heating		Wristpad cooling	
(Chair+Insole+ Wristpad) heating		(Chair+Insole+ Wristpad) cooling	

2.3 Determining PCS subjective comfort effects using human tests

CP may also be measured by human subject testing. The results may be presented in terms of the ambient temperature difference under which subjects report equal thermal sensation with and without PCS, or in terms of the difference in the survey scale units used to measure

subjects' thermal sensations and comfort [13]. The following tests were carried out for our suite of PCS devices.

Subjects. Twenty healthy college-aged subjects (10 females and 10 males) were recruited to participate in tests of the PCS devices under warm and cool conditions. The male and female groups comprised an almost identical proportion of Caucasian (7F/6M) and Asian ethnicities (3F/4M). Subjects' characteristics are presented in Table 2. Female subjects tended to have less body mass and be shorter than male subjects. Clothing levels are the same as described in the manikin tests: 0.65 Clo for cool condition and 0.5 Clo for summer condition.

All the subjects had light-to-none caffeine, alcohol, smoking habits and normal exercise intensity (2~4 times per week). They were trained in advance to be familiar with how to use the devices and were informed that they would experience mild cool and warm exposures prior to the formal test. The experimental protocol was reviewed by University of California Berkeley's Committee for the Protection of Human Subjects (Approval # 2015-08-7882).

Table 2. Subjects' profile, including age, mass, height, and body surface area, are reported for the male and female groups. Body surface areas are calculated by Dubois formula [34]. Statistical differences between groups for each characteristic were assessed by means of independent group t-tests, with cut-off probability value for significance set at p=0.05.

	Age (year)	Mass (kg)	Height (m)	Body mass index (BMI)	Body surface area (m^2)
Male	24 ± 3.2	67 ± 3.2	1.72 ± 0.2	22.6±0.3	1.79 ± 0.2
Female	23 ± 3.8	59 ± 3.8	1.63 ± 0.2	22.2±0.4	1.63 ± 0.1
Probability	0.457	0.032	0.041	0.061	0.025

Test conditions. Table 3 shows the test conditions. In total, 7 heating scenarios and 4 cooling scenarios were tested in 3 climate chamber experiments. Each experiment lasted for 130 min. Since the heated/cooled chair had been previously evaluated by Pasut et al. [24,25], the chair-alone condition was not repeated and Pasut's results were incorporated into the data analysis. Also, the small deskfan was incorporated as a given element into each cooling scenario. Facial ventilation is the single most noticeable cooling need, often determining whole-body comfort in warm environments by itself. It makes practical sense to include it as a common denominator in PCS cooling scenarios, because very effective USB fans are now widely

available, inexpensive, quiet and unobtrusive on the desktop, highly energy-efficient, and easy to use.

Table 3. Human subject tests

Heating scenarios (18°C, 40% RH)	**Test scene**	**Cooling scenarios (29°C, 40% RH)**	**Test scene**
Reference condition		Reference condition	
Insole		Deskfan + Wristpad	
Wristpad		Deskfan + Chair	
Insole + Wristpad		Deskfan + Wristpad + Chair	
Insole + Chair			
Wristpad + Chair			
Insole + Wristpad + Chair			

Test procedure, survey questionnaire, and skin temperature measurement. Figure 2 shows the test protocol exemplified by the cooling scenario. Each subject participated in four test sessions after a 30-minute acclimation period. Each test session lasted 20 minutes and was followed by a 5 minutes break interval. The sequence of the test sessions depended on the heating/cooling capacity of the devices or combination of devices. Previous tests suggested that the chair might dominate whole-body sensation [24,25]. Therefore, the lower heating/cooling capacity test sessions were put first, followed by the stronger heating/cooling combinations. If two sessions had similar heating/cooling capacity, they were randomly ordered. The reference session, with no heating or cooling, was randomly inserted between other test sessions. For cooling test, one 130-min experiment was needed for the 4 scenarios. For heating tests, two 130-min experiments were needed for the 7 scenarios.

In each test, participants used the CBE (Center for the Built Environment, University of California, Berkeley) thermal comfort questionnaire tool [29], reporting the magnitude of thermal acceptance, whole-body and local thermal sensations, and whole-body and local thermal comfort. Question-answering happened at the 0th, 2nd, 4th, 12th and 20th minute of each session (as shown by the inverted triangles).

Skin temperatures at different body parts were monitored throughout the tests. This was done to track the thermal effects of the local heating and cooling on the body, and to evaluate how the devices were performing. For heating scenarios, ten temperature sensors (WZYCH4,

Tianjianhuayi, China) with 0.1°C accuracy were taped to eleven local body sites (cheek, forearm, abdomen, lower back, thigh, dorsal hand, finger, left and right lower leg, left and right dorsal foot). The sensing sites positions followed those of Gagge and Nishi [35]. They are standard test locations, not directly at the locations where heating or cooling are applied by the devices. The sensors on both left and right lower leg and foot are for tests where only one insole was heated, to compare the insole heating effect. For cooling scenarios, for which there was no insole test, skin temperatures were measured on the left leg, left foot, forehead and the remaining 9 body parts. Subjects' clothing insulation was maintained the same as in the manikin test, 0.65Clo for heating and 0.5Clo for cooling.

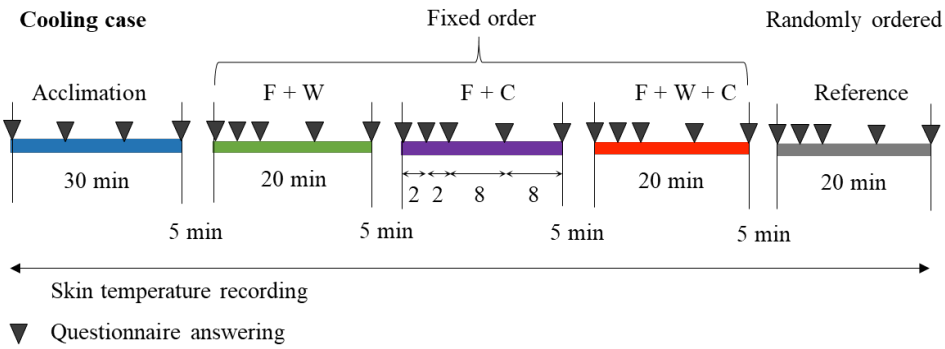


Figure 2. Test protocol example for cooling case

3 RESULTS

3.1 Heat transfer performance from manikin tests

Figure 3 gives each device's wattage and temperature CP values, for the individual body parts. For example, the chair mainly affects areas of the pelvis, back, and thigh. By itself, the chair can elevate the thigh heat loss by 5.3W (or EHT by 5.2K) in the warm condition and decrease its heat loss 3.7W (or increase EHT by 3.7K) in the cold condition. Other devices like the wristpad mainly target the forearm and hand, the insole warms only the foot, and the deskfan enhances heat dissipation on the upper body parts (head, chest, and upper arm).

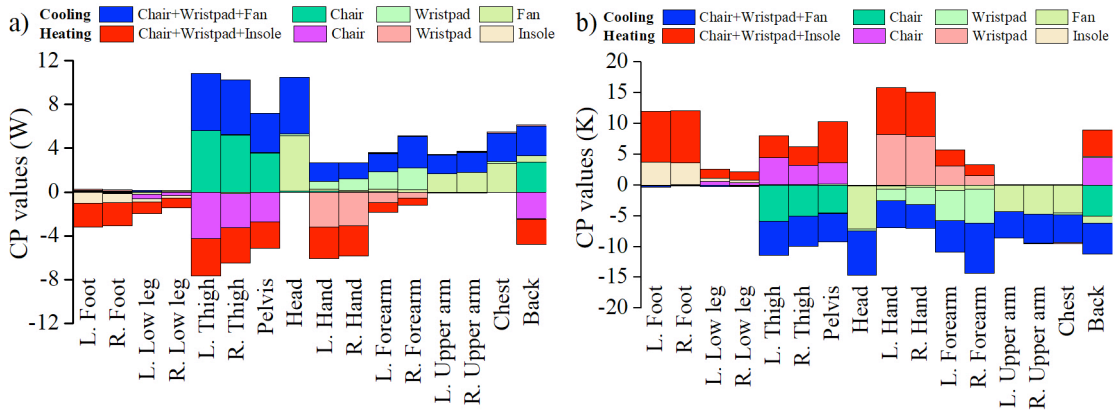


Figure 3. CP values by body part: a) CP in terms of local heat loss, b) CP in terms of EHT.

Table 4 summarizes the *whole-body* heating and cooling effects of PCS devices. In terms of EHT, chair cooling alone can compensate for 2K ambient temperature deviation (first row in Table 3). Combining all three cooling devices, the corrective power is as high as 4.2K. With CP in terms of watts (second row in Table 4), the deskfan cooling alone increases heat loss by 12.3W, while combining the three cooling devices dissipates 36W. Finally, the COP quantifies each device's energy efficiency. For the deskfan cooling, 1 watt of electrical energy produces 6.2 watts of human body heat dissipation and thus the COP of fan cooling is as high as 6.2 (third row in Table 4). The heating performance is seen in the lower part of the table. Heating COPs cannot be as high as cooling COPs, because fan cooling uses its electrical power to amplify natural convective heat loss to ambient air, whereas these heating devices use their electrical input to directly offset body heat losses. Therefore, the maximum ideal COP value should be 1. One should note that insulation reduces normal body heat losses without the need for electrical input. The reflective material at the bottom and the back in the chair alone corrects ambient temperature 0.44K and reduces human body heat loss by 3.78W, compared to the chair tested without the reflective layer.

Table 4. COP and whole-body corrective power of PCS devices from thermal manikin tests. The combination of the four devices can correct the ambient temperature towards thermal neutrality by 4.2K cooling and 2.7K heating with a combined heating COP of 0.88 and cooling COP of 3.6.

	Metrics	Deskfan	Wristpad	Chair	Chair + Deskfan + Wristpad
Cooling performance	$CP_{EHT_{whole-body}}$ (K)	1.45	0.52	2.01	4.24
	CP_Q (W)	12.33	4.47	17.13	36.13

	COP	6.2	2.2	2.9		3.6
Heating performance	Metrics	Insole	Wristpad	Chair	Reflective material on Chair	Chair + Insole + Wristpad
	$CP_{EHT_{whole-body}}$ (K)	0.26	0.75	1.25	0.44	2.66
	CP_Q (W)	2.22	6.38	10.68	3.78	22.25
	COP	0.92	0.71	0.67	---	0.88

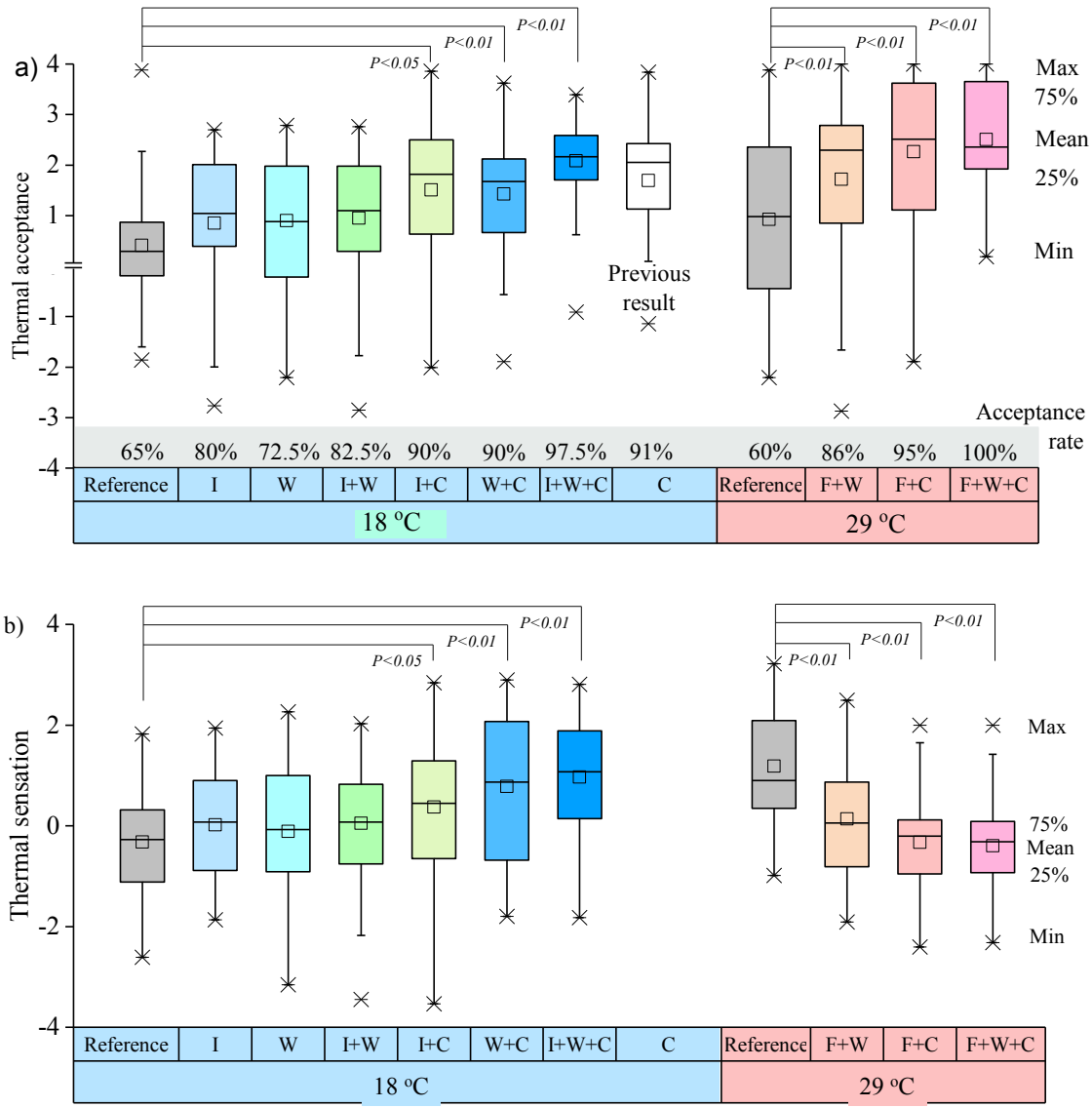
3.2 Thermal performance of PCS devices from human subject tests

3.2.1 Subjective responses to PCS. Figure 4 summarizes the thermal comfort effects of the 4 PCS devices in terms of acceptance of the environment, and whole-body- and local-body thermal sensations. Figure 4a gives the whole-body acceptance vote of different heating and cooling combinations. The vertical axis represents acceptance vote, ranging from clearly unacceptable (-4) to clearly acceptable (+4). The overall acceptance rates are calculated as the percentage of votes located on the acceptable side (from 0 to +4) of total votes.

At 18°C, with no PCS devices provided, the acceptance rate was 65% (grey box). As insole, wristpad, and chair heating were introduced, the acceptance rate rose to 97.5%. Wristpad-and insole-heating were less effective at increasing acceptance rate than the chair. Subject comments suggest that though the wristpad warmed the wrist locally, the fingers were not warmed enough. At 29°C, without PCS, many acceptance votes are located on the unacceptable side, for an overall acceptance rate of 60%. As subjects could use some combinations of deskfan, wristpad, and chair cooling, their acceptance vote is improved significantly, to 86%, 95%, and 100% respectively; each of these is higher than the 80% goal for thermal environmental standards [36] (ASHRAE 55, 2017).

Figure 4b shows the statistics of subjects' thermal sensation vote (TSV) in each cooling and heating combination. The vertical axis represents TSV ranging from very cold (-4) to very hot (+4). In the 18°C cold condition, PCS raised subjects' whole-body sensation from cool to neutral and slightly warm. The grey box represents the reference case without PCS. Combining PCS devices increased their heating effect. Under the 29°C warm condition, the PCS devices lowered (cooled) subjects' whole-body thermal sensation from warm to neutral and slightly cool, again with additive effect. Such measured differences in thermal sensation could be regarded as CP_{TSV} for the devices under slightly cool (18°C) and slightly warm (29°C) ambient conditions.

Since the four PCS devices add their heat and cooling locally to different body parts, the local-body-part thermal sensations in Figure 4c provide perspective into the thermal comfort effects of the different devices. The grey boxes are reference case without PCS devices. At 18°C, PCS devices warmed up the foot, hand and seat area. The local improvements are generally larger than the whole-body improvements. For example, the insole by itself can lift the foot thermal sensation vote by 2.1 scale units but does not significantly change the whole-body sensation (Fig 4b). In 29°C the grey boxes are 1~2 sensation scale-units warmer than the colored boxes indicating the cooling of the hand, face and seat areas. Comparing 4b and 4c shows that the whole-body sensation closely follows the local sensation of the cooled part.



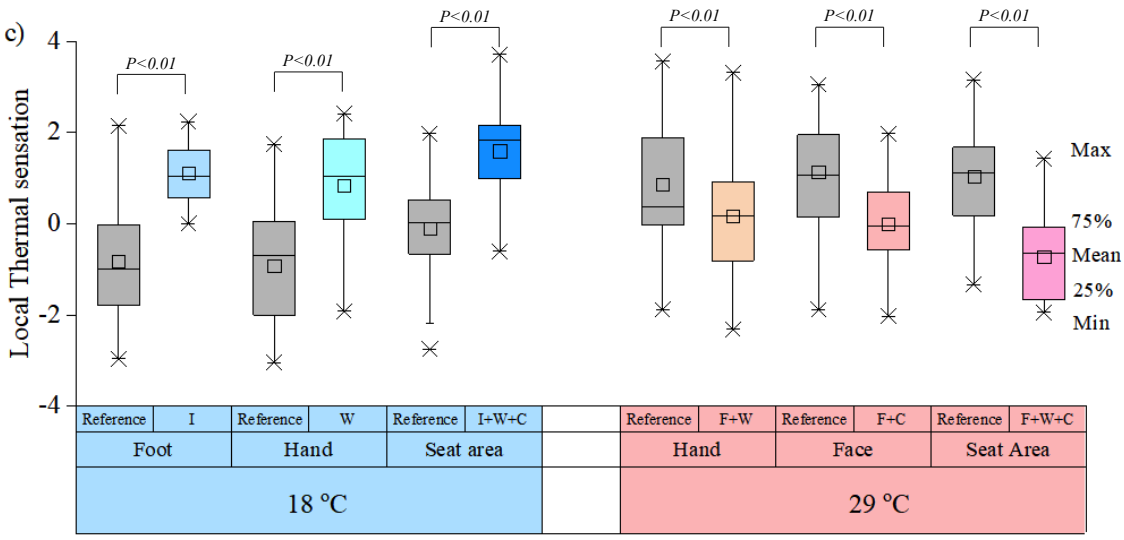


Figure 4. Thermal comfort effects of PCS devices, a) Whole-body thermal acceptance, b) Whole-body thermal sensation, c) Local thermal sensation examples. (Note: the voting results shown in this figure represent the last two votes of each test session. The labels in horizontal axis are abbreviations of insole (I), wrist-pad (W), chair (C), and fan (F) respectively. Statistical differences between groups were assessed by means of paired group t-tests, with cut-off probability value for significance set at p=0.05).

3.2.2. Subjective responses grouped by individuals' thermal sensitivity. Figure 5 tracks subjects' whole-body TSV and TCV for the different PCS devices. Subjects are clustered into three groups based on their TSV prior to using the PCS devices, after 30 minutes of exposure to the ambient test condition. The 'cool group' refers to the 25% percentile of subjects who felt colder than others while the 'warm group' refers to the 25% percentile of subjects who felt warmer. It is interesting to observe that 4 of the 5 people in each of the 'cool' and 'warm' groups were the same throughout all the test conditions.

Figure 5a shows that there is a difference of 2.5~3 TSV units between the warm and cool groups in both heating (18°C) and cooling (29°C) conditions. The suite of PCS devices warmed the 'cool group' by 1.8 TSV units, more than it warmed the 'warm group' (0.8 TSV units). Presumably the warm group does not need warming but this indicates the range of sensation that is possible, or that would occur if personal control were not available. In cooling, the PCS cooled the 'warm group' by up to 1.5 TSV scale units. The cool group cools a similar amount, indicating that availability of personal control will be more important for cooling PCS than for heating PCS.

Figure 5b shows that the difference between uncomfortable and comfortable groups is 3.8 without PCS, decreasing to 2.1 with all PCS devices added. That shows that the smaller PCS devices by themselves were not able to satisfy the uncomfortable group, but combinations of PCS were able to shift the uncomfortable group into comfort and reduce the comfort difference between the comfortable and uncomfortable groups. Comparatively, the comfort improvement provided by these PCS devices is greater for cooling than for heating.

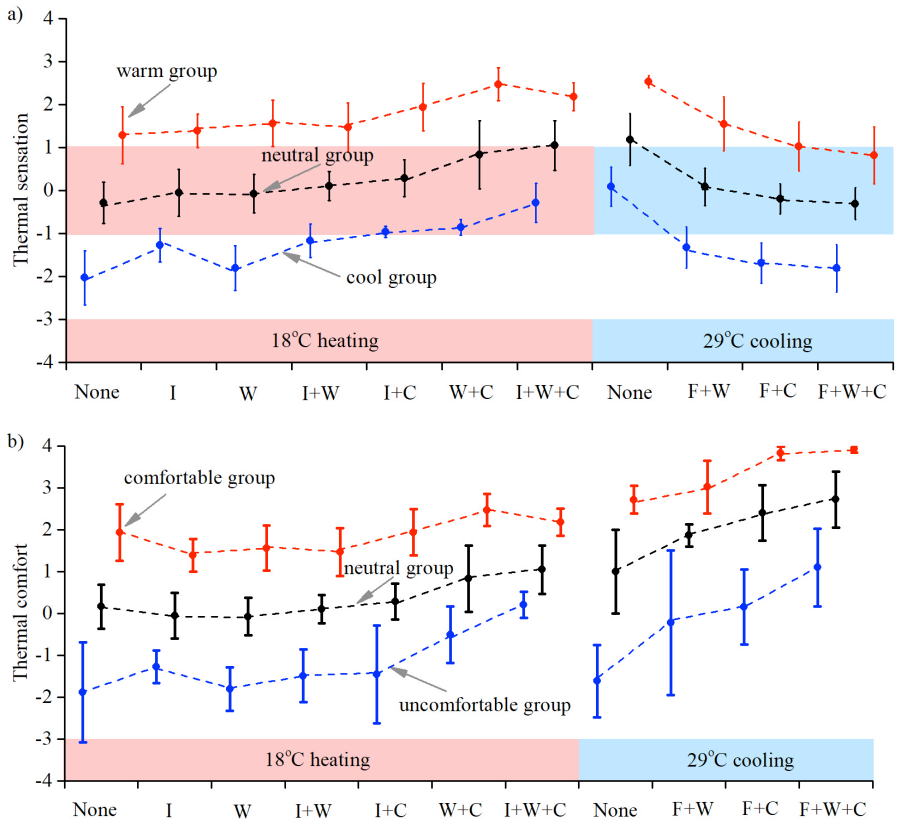


Figure 5. Effect of PCS on different subject groups: a) whole-body thermal sensation (cool group: TSV vote below 25 percentile, neutral group: TSV vote between 25 and 75 percentile, warm group: TSV vote above 75 percentile); b) whole-body thermal comfort (uncomfortable group: TCV vote below 25 percentile, neutral group: TCV vote between 25 and 75 percentile, comfortable group: TCV vote above 75 percentile)

3.2.3. Physiological responses; skin temperatures. The physical measurement of subjects' skin temperatures indicates the amount of heating/cooling taking place, affected both by individual posture/position relative to the PCS and by their thermophysiological response to the thermal conditions imposed. Figure 6 shows four subjects' local skin temperature profiles during the tests. There are substantial inter-subject differences in the skin temperature of local body parts resulting from how the subject utilized the PCS device. In the case of chair

heating/cooling, some subjects leaned their upper body against the chair back less often than others, influencing the extent of back heating/cooling. Some of the differences come from the fact that different PCS devices target particular body parts. The insole warms the feet, while the wristpad mainly affects the hand.

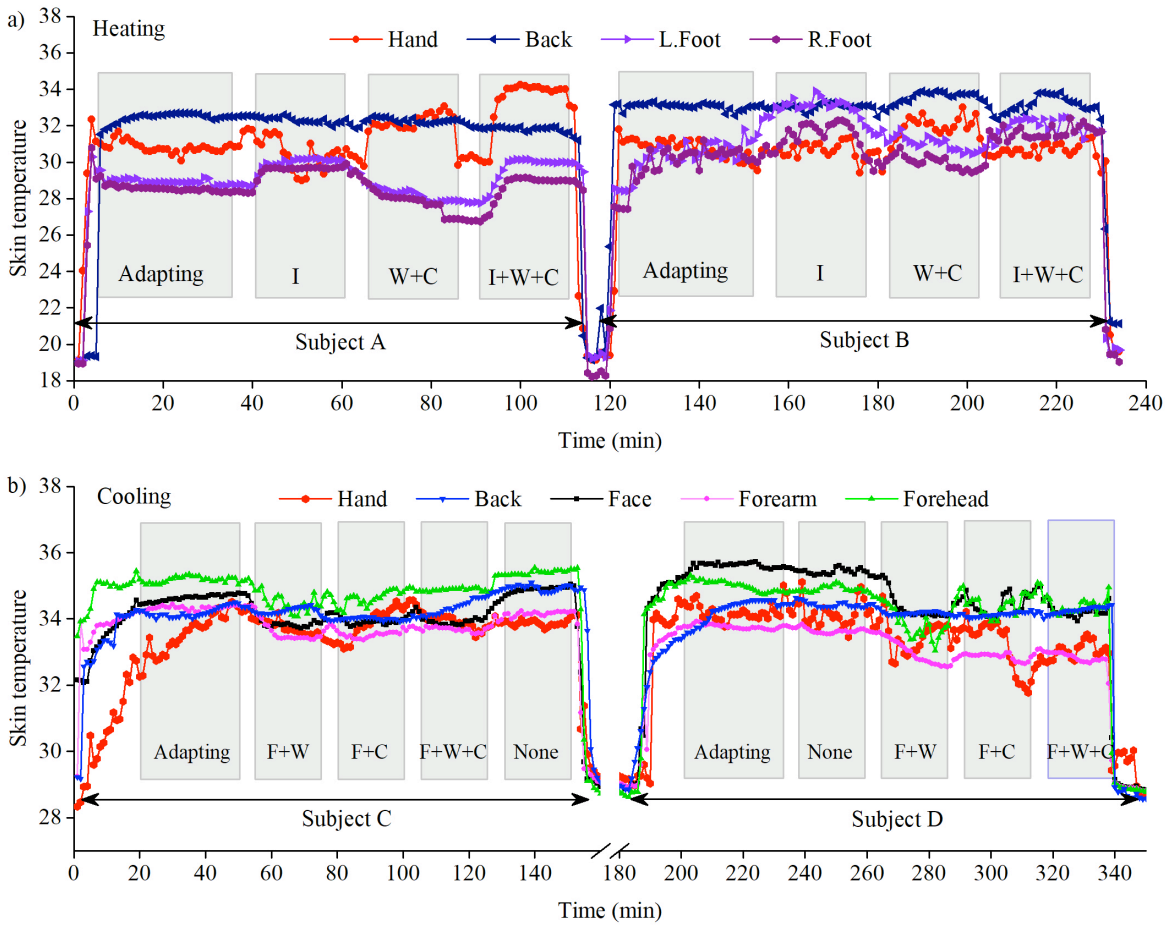


Figure 6 Local skin temperature profiles under different PCS applications, a) heating scenario, b) cooling scenario (note, this figure displays only the body parts directly affected by the PCS devices. The skin temperatures are from standard sites representing the whole-body part, and are not from areas directly contacted by the PCS device.)

Figure 7 represents the full set of measured local skin temperatures, for the body parts affected by the different PCS applications. Skin temperature changes shown in the vertical axis are calculated from the skin temperature with a PCS minus the skin temperature at the reference case. Positive values represent higher skin temperatures than in the reference case and vice versa. In the red frames for 18°C ambient, the heating function of the insole, wristpad, and chair warm the hand, finger, and feet. The skin temperatures in these body parts are significantly higher than the reference case, while those on other body parts not directly

heated (e.g. face, belly) are unchanged. Similar phenomena can be observed in the red frames for 29°C ambient. The cooling of deskfan, wristpad, and chair affects the face, forehead, hands, and forearms. Note that the cooling provided by the back of the chair can be seen to be small, but the chair back is important in heating mode.

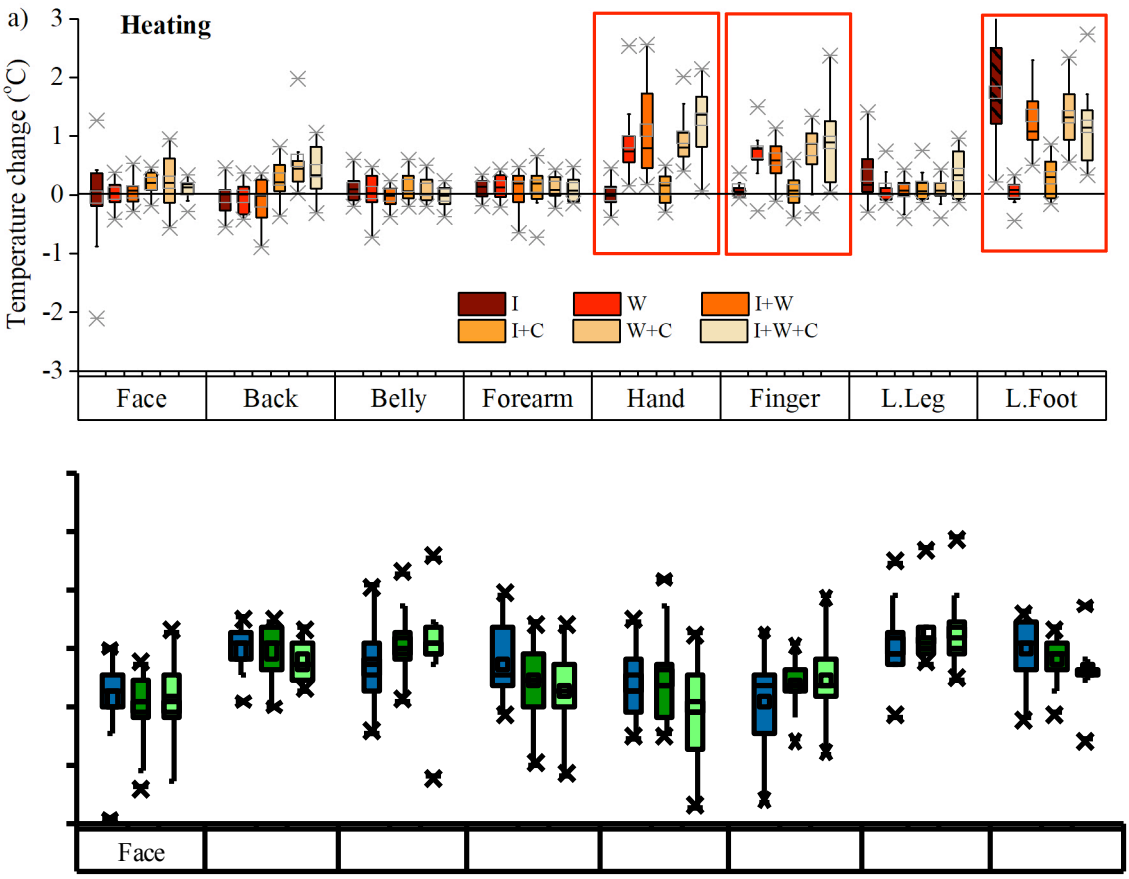


Figure 7. Skin temperature changes caused by PCS devices, a) heating scenarios, b) cooling scenarios.

4 DISCUSSION

4.1 Corrective Power of PCS on the affected body parts and on the whole body

PCS may act to prevent discomfort from occurring locally in individual body parts that are affected as the whole body drifts out of thermal neutrality. Local discomfort occurs as the body resorts to vasoconstriction (cold feet, lower legs, and hands) or strong vasodilation or sweating (warm face and torso) to restore neutrality. Vasoconstriction and vasodilation may occur in uniform thermal surroundings, or in non-uniform environments such as rooms with radiant heating/cooling surfaces, solar gain, or temperature stratification. Local discomfort in a single body part often determines whole-body thermal comfort perception [16,37,38]. By adding localized heating and cooling directly to such a part and modifying the skin

temperature as in Figure 6 and 7, PCS may activate spatial alliesthesia and eliminate the source of whole-body discomfort

Table 5 lists the corrective power of our PCS devices on their targeted local body parts, both in terms of EHT correction from the manikin tests, and local TSV and TCV improvements from the human subject tests shown in Fig 4. The PCS devices are seen to provide 4.1~7.2 K cooling correction and 6.1~8.3 K heating correction to local body parts, 1.2~1.8 and 1.2~2.0 local cooling and heating sensation correction (in TSV scale units), and 0.5~1.1 and 1.2~1.9 local cooling and heating comfort correction (TCV scale units). The face and pelvis are seen to be important for cooling while the foot and hand are important for heating.

Table 5. Local heating and cooling CP values from PCS

	Body part	CP_{EHT} (K)	TSV improvement	TCV improvement
Cooling (Chair + Deskfan + Wristpad)	Pelvis	-5.0	-1.8	0.9
	Face	-7.2	-1.2	1.1
	Hand	-4.1	-1.2	0.5
	Chest	-4.5	-1.1	0.8
	Back	-5.1	-1.2	0.9
	Whole-body CP_{EHT} (manikin test)	**-4.2**		
	Whole-body CP_{TSV} (human tests)	**-6.5 (CBE Comfort Tool) -5.1 (using 3K/TSV)**	**-1.7**	**1.7**
Heating (Chair + Insole + Wristpad)	Foot	8.3	2.0	1.9
	Pelvis	6.7	1.7	1.3
	Hand	7.4	1.8	1.6
	Back	6.1	1.2	1.2
	Whole-body CP_{EHT} (manikin test)	**2.7**		
	Whole-body CP_{TSV} (human tests)	**3.6 (CBE Comfort Tool) 3.6 (using 3K/TSV)**	**1.2**	**1.7**

Table 5 also presents whole-body CP values in temperature units, calculated from subjectively-determined TSV improvement (CP_{TSV}[a]), and from manikin-obtained EHT

[a] Table 5 presents two ways to calculate CPTSV in temperature units (K). They are not directly comparable but give similar results.

a) Using the CBE Comfort Tool (http://comfort.cbe.berkeley.edu/), the neutral ambient temperatures for summer (0.5clo) and winter (0.65clo) are 25.4°C and 24.5°C respectively. Figure 4b shows that, for 75% of the population, the combined devices corrected TSV to neutral or beyond in both the cooling (29°C) and heating (18°C) tests. Therefore, the CP is 3.6K for cooling (29°C - 25.4°C) and 6.5K for heating (24.5°C -18°C).

corrections (CP_{EHT}). The CP_{TSV} values are substantially greater than the CP_{EHT} values. At least two processes contribute to this.

First, whole-body TSV may be more sensitive than whole-body EHT because people with PCS are experiencing spatial alliesthesia when they vote TSV. A manikin unable to experience alliesthesia would require a greater temperature change to achieve the same improvement to TSV. Second, because most thermal manikins (including the one in this study) cannot emulate sweating, they cannot account for whatever latent heat is dissipated from the skin by PCS devices, especially in the cooling condition (29°C).

In future PCS development and evaluation, CP_{EHT} or CP_{TSV} might serve as standard performance indicators. Manikin testing is more feasible in commercial practice than human subject testing. From Table 4, we can expect the CP_{EHT} values to be conservative for both cooling and heating. For the PCS devices in this study, relating CP_{EHT} to CP_{TSV} requires a coefficient of 1.55 for cooling and 1.33 for heating.

4.2 Ability of PCS to correct for individuals' thermal comfort differences seen in field studies

The corrective power of our PCS seen in Figure 5 and Table 5 PCS must at the least compensate for individual's thermal differences in the same thermal condition. These differences arise from: *a)* the inter-personal variance among people [39] (attributed to factors such as gender [40], body mass [41], age [42], dress custom, and activity level [43], and *b)* the intra-personal variation in thermal perceptions of a single person over time. From field studies in real buildings, the variance in individual thermal sensation tends to be around 1 TSV scale unit on the ASHRAE seven-point scale [44], ranging from 1.2 in cool conditions to 0.9 in warm conditions (Figure 9).

---

b) Using Humphreys' 3K/TSV coefficient [44], the measured 1.7 TSV unit change for cooling is equivalent to 5.1K CP, and the 1.2 TSV unit change for heating is equivalent to 3.6K CP.

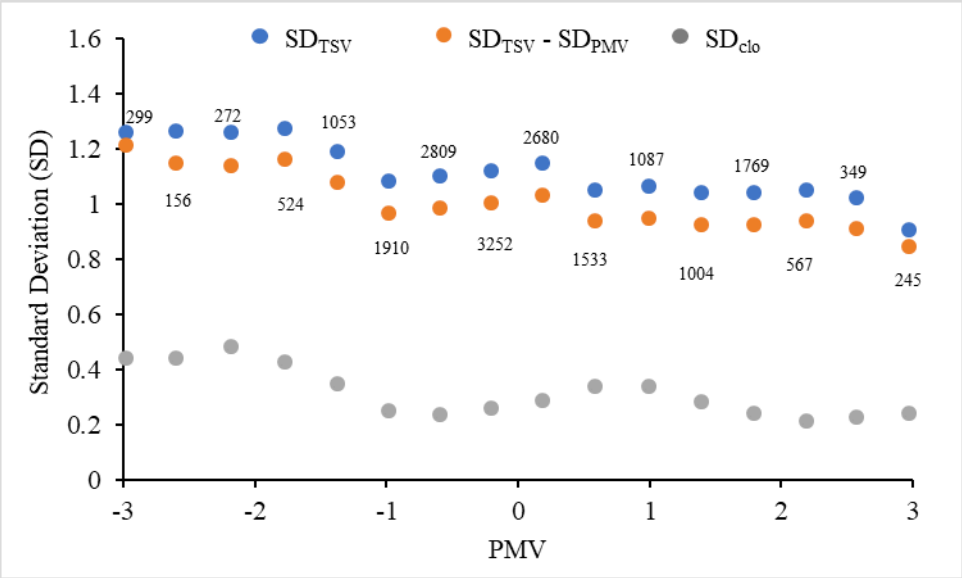


Figure 8. Individual differences in building occupants' thermal sensation. The data source is from RP-884 thermal comfort database [45]. The numbers besides the dots represent sample sizes. The X-axis is PMV, binned within ±0.2 PMV scale units. The Y-axis is Standard Deviation. SD_{TSV} (blue dots) represents the magnitude of TSV variance within the bin. Considering that thermal environment within ±0.2 PMV contains the variance SD_{PMV}, SD_{TSV}-SD_{PMV} (orange dots) represents the individuals' TSV variance corrected by the PMV variance. It ranges from 0.9TSV in warm conditions (PMV = 3) to 1.2TSV in cool (PMV = -3). The larger standard deviation at low PMVs can be explained by the larger variation in clothing in cool conditions (gray dots).

With one TSV scale unit roughly equivalent to 3K ambient temperature (or the full width of the ASHRAE comfort zone) the magnitude of these differences makes it both challenging and energy-consuming for a conventional HVAC system to provide thermal conditions satisfying all occupants. The PCS corrective powers obtained by the laboratory subject tests (3.6K heating plus 5.1-to-6.5K cooling, totalling 8.7 – 10.1K) are capable of compensating for about two SDs of individual variation, covering 95% of the population in near-neutral conditions.

4.3 Energy-saving potential of PCS in the building context

In addition to its internal energy efficiency as measured by COP, PCS makes possible major energy reductions in building conditioning. A field study shows that by providing personal comfort devices and adjusting HVAC supply airflow setpoints, occupants' satisfaction rate increased from 56% to over 80%, while lowering HVAC zone energy use by 60% in heating

and 40% in cooling [46]. A relatively small amount of PCS heating/cooling energy leads to comfort improvements even at ambient temperatures below and above the conventional neutral temperature. The power required by PCSs (between 10 to 15 W) offsets roughly 500 to 1000 W [b] per occupant for the same effect provided by the building's HVAC system. This is a one to two orders of magnitude improvement.

Figure 9 shows a method to estimate the energy saving potential of PCS devices. In the figure, the solid lines are extracted from the building simulation study by Hoyt et al. [4], indicating savings in total annual HVAC energy consumption caused by widening the temperature dead-band of the HVAC system. The heating and cooling corrective powers of the PCS are added. The dashed lines indicate HVAC energy savings subtracting the energy consumed by the PCS devices themselves. The tiny differences between the solid and dash lines suggest that the energy used by this suite of PCS can be neglected when evaluating the energy use of the HVAC system. The savings for different climates are summarized in Table 6.

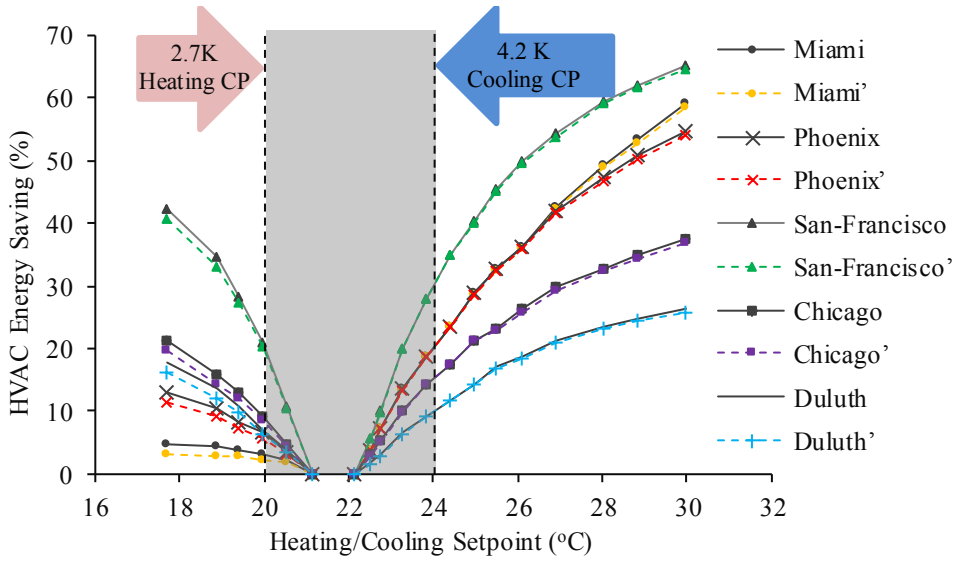


Figure 9. Potential energy saving of PCS devices. (Adapted from Hoyt et al. [4])

Table 6. Estimated energy saving of this study's PCS in different climate conditions

[b] This number is estimated from the total electricity consumption (3080 trillion btu) of space heating, cooling, and ventilation in U.S. commercial buildings in 2012, the amount of workers (88.182 million), the energy saving potential of PCS (about 10%~20%) listed in Table 6.

Cities	Heating scenario (18°C)	Cooling scenario (29°C)
Miami	1.5%	34.1 %
Phoenix	6.4%	31.5 %
San-Francisco	20.7%	33.7 %
Chicago	9.7%	20.1 %
Duluth	9.2%	15.3 %

5 CONCLUSIONS

This study investigates the heating and cooling performance of four PCS devices developed by CBE.

(1) Applications of these PCS devices significantly improved subjects' whole body thermal acceptance and thermal comfort perception in the non-neutral experimental conditions of 18°C and 29°C. The comfort benefit of PCS devices can be attributed to: 1) covering individual thermal comfort differences, 2) preventing local discomfort from occurring in individual body parts. The activation of spatial alliesthesia will contribute to the comfort perceived.

(2) PCS devices can provide local heating and cooling directly to the human body with great efficiency. These low-power devices each uses only 2 to 14 W. Thermal manikin tests show that the four devices have a combined heating COP of 0.88 and cooling COP of 3.6.

(3) The PCS devices have corrective power of up to 2.7K heating and 4.2K cooling, in terms of shifting the EHT towards neutral in manikin tests; or up to 3.6K heating and 6.5K cooling based on human subject tests.

(4) The energy-saving potential of PCS devices is promising because they allow the currently tight control of building temperatures to be loosened. For US cities in different climate zones, the application of the heating PCS devices can save 1.5%~20.7% of total HVAC energy, while the cooling devices can save 15.3%~34.1% of total HVAC energy.

ACKNOWLEDGEMENT

This paper is extended from a conference manuscript submitted to Indoor Air 2018. The research was supported by the ARPA-E (Advanced Research Projects Agency-Energy, Department of Energy) DELTA (Delivering Efficient Local Thermal Amenities) program under contract DE-AR0000529. We also thank Noah Pitts and Megan Zhu for creating the test apparatus, and the 20 subjects who participated in the study.

6 REFERENCES

[1] US EIA. Annual Energy Outlook 2017. https://www.eia.gov/outlooks/aeo/. (Accessed on2018/1/30).

[2] European Parliament and Council. (2010) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Official Journal of the European Union. 153: 13-35.

[3] Xiong W, Wang Y, and et al. (2015) Heat roadmap China: New heat strategy to reduce energy consumption towards 2030. Energy. 81: 274-285.

[4] Hoyt T, Arens E, Zhang H. (2015) Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. Building and Environment. 88: 89-96.

[5] Ghahramani A, Zhang K, Dutta K, et al. (2016) Energy savings from temperature setpoints and deadband: quantifying the influence of building and system properties on savings. Applied Energy. 165: 930-942.

[6] Arens E, Humphreys M, de Dear R, Zhang H. (2010) Are 'class A' temperature requirements realistic or desirable? Building and Environment. 45: 4-10.

[7] Zhang H, Arens E, and Pasut W. (2011) Air temperature thresholds for indoor comfort and perceived air quality. Building Research and Information 39(2): 134-144.

[8] Bauman F, Carter T, Baughman A, Arens E. (1998) Field study of the impact of a desktop task/ambient conditioning system in office buildings. ASHRAE Transactions. 104: 1153-1171.

[9] Zhang H, Arens E, Taub M, Dickerhoff D, Bauman F, et al. (2015a) Using footwarmers in offices for thermal comfort and energy savings. Energy and Buildings 104; 233-243.

[10] Cabanac M, Massonnet B, and Belaiche R. (1972) Preferred skin temperature as a function of internal and mean skin temperature. Journal of Applied Physiology. 33 (6): 699–703.

[11] Hensel H. (1982) Thermal sensation and thermoreception in man. Charles C Thomas, Springfield, III.

[12] Ring J, de Dear R. (1991) Temperature transients: a model for heat diffusion through the skin, thermoreceptor response and thermal sensation. Indoor Air. 4: 448-456.

[13] Zhang H, Arens E, Zhai Y. (2015b). A review of the corrective power of personal comfort systems in non-neutral ambient environments. Building and Environment. 91: 15-41.

[14] Parkinson T, and de Dear R. (2015) Thermal pleasure in built environments: physiology of alliesthesia. Building Research & Information. 43(3): 288-301.

[15] Parkinson T, de Dear R and Candido C. (2016) Thermal pleasure in built environments: alliesthesia in different thermoregulatory zones. Building Research & Information. 44(1): 20-33.

[16] Zhang H. (2003) Thermal comfort for non-uniform and transient conditions. PhD thesis. UC, Berkeley.

[17] Arens E, Zhang H, Huizenga C. (2006) Partial- and whole-body thermal sensation and comfort— Part I: Uniform environmental conditions. Journal of Thermal Biology. 31: 53-59.

[18] Zhang H, Arens E, Huizenga C, Han T. (2010c). Thermal sensation and comfort models for non-uniform and transient environments: Part III: whole-body sensation and comfort. Building and Environment, 45(2), 399 - 410.

[19] Veselý M, Zeiler Wim. (2014) Personalized conditioning and its impact on thermal comfort and energy performance – A review. Renewable and Sustainable Energy Reviews. 34: 401-408.

[20] Luo M, Cao B, et al. (2016) The underlying linkage between personal control and thermal comfort: Psychological or physical effects? Energy and Buildings. 111(1): 56-63.

[21] Shahzad S, Calautit J, Aquino A, et al. (2017) A user-controlled thermal chair for an open plan workplace: CFD and field studies of thermal comfort performance. Applied Energy. 207: 283-293.

[22] Veselý M, Molenaar P, et al. (2017) Personalized heating – Comparison of heaters and control modes. Building and Environment. 112(1): 223-232.

[23] He Y, Li N, et al. (2017) Thermal comfort and energy consumption in cold environment with retrofitted Huotong (warm-barrel). Building and Environment. 112(1): 285-295.

[24] Pasut W, Arens E, et al. (2014) Enabling energy-efficient approaches to thermal comfort using room air motion. Building and Environment. 79: 13-19.

[25] Pasut W, Zhang H, et al. (2013) Effect of a heated and cooled office chair on thermal comfort. HVAC&R Research. 19: 574-583.

[26] Arens H, Zhang H, Pasut W (2015) Patent: Heated and cooled chair apparatus, approved 2015. (US 14/816234)

[27] Watanabe S, Shimomura T, Miyazaki H. (2009) Thermal evaluation of a chair with fans as an individually controlled system. Building and Environment. 44:1392-1398.

[28] Huang L, Arens E, et al. (2014) Applicability of whole-body heat balance models for evaluating thermal sensation under non-uniform air movement in warm environments. Building and Environment. 75:108-113.

[29] Zhai Y, Zhang H, et al. (2013) Comfort under personally controlled air movement in warm and humid environments. Building and Environment. 65:109-117.

[30] Arens E, Zhang H, Kim D, et al. (2008) Impact of a task-ambient ventilation system on perceived air quality. Indoor Air 2008, August 17-22, Copenhagen, Denmark.

[31] Wyon P, Larsson S, et al. (1989) Standard procedures for assessing vehicle climate with a thermal manikin. Tech. rep. SAE Technical Paper 890049.

[32] McGuffin R, Burke R, et al. (2002) Human thermal comfort model and manikin. SAE Technical Paper 2002-01-1955.

[33] Tanabe S., Arens E, Bauman F, et al. (1994) Evaluating thermal environments by using a thermal manikin with controlled skin surface temperature. ASHRAE Transactions. 100 Part 1: 39-48.

[34] DuBois D, DuBois EF. (1989) A formula to estimate the approximate surface area if height and weight be known. Nutrition. 5(5): 303-11.

[35] Gagge A and Nishi Y. (1977) Heat exchange between human skin surface and on a simple model of human physiological regulatory response. ASHRAE Transactions. 77(1): 247-262.

[36] ASHRAE. (2017) Thermal environmental conditions for human occupancy. ANSI/ASHRAE Standard 55. Atlanta: ASHRAE, Inc.

[37] Cheong K, Yu W, Sekhar S, et al. (2007) Local thermal sensation and comfort study in a field environment chamber served by displacement ventilation system in the tropics. Building and Environment. 42(2): 525-533.

[38] Cui W, Ouyang Q, and Zhu Y. (2014) Field study of thermal environment spatial distribution and passenger local thermal comfort in aircraft cabin. Building and Environment. 80: 213-220.

[39] Wang Z, de Dear R, et al. (2018) Individual Difference in Thermal Comfort: A Literature Review. Building and Environment. 138(15): 181-193.

[40] Karjalainen S. (2012) Thermal comfort and gender: a literature review. Indoor Air. 22(2): 96-109.

[41] Havenith G, Luttikholt V, Vrijkotte T. (1995) The relative influence of body characteristics on humid heat stress response. European Journal of Applied Physiology and Occupational Physiology. 70(3): 270-279.

[42] Indraganti M and Rao K. (2010) Effect of age, gender, economic group and tenure on thermal comfort: a field study in residential buildings in hot and dry climate with seasonal variations. Energy and Buildings. 42(3): 273-281.

[43] Luo M, Wang Z, et al. (2018) Human metabolic rate and thermal comfort in buildings: The problem and challenge. Building and Environment. 131: 44-52.

[44] Humphreys M and Nicol J. (2002) The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. Energy and buildings. 34(6): 667-684.

[45] de Dear R. (1998) A global database of thermal comfort field experiments. ASHRAE Transactions. 104: 1141-1152.

[46] Zhang H, Bauman F, Arens E, et al. (2018) Reducing building over-cooling by adjusting HVAC supply airflow setpoints and providing personal comfort systems. Indoor Air 2018, July 22 – 27, Philadelphia, PA, USA.