Building and Environment 244 (2023) 110787

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Thermal comfort and energy efficiency evaluation of a novel conductive-radiative Personal Comfort System

Roberto Rugani [a,*], Marco Bernagozzi [b], Marco Picco [b], Giacomo Salvadori [a], Marco Marengo [c], Hui Zhang [d], Fabio Fantozzi [a]

[a] *Department of Energy, Systems, Territory and Constructions Engineering (DESTeC), University of Pisa, Pisa, Italy*
[b] *Advanced Engineering Centre, University of Brighton, Brighton, United Kingdom*
[c] *Department of Civil Engineering and Architecture, University of Pavia, Pavia, Italy*
[d] *Center for the Built Environment (CBE), University of California Berkeley, Berkeley, CA, USA*

A R T I C L E I N F O

Keywords:
Thermal comfort
Building energy saving
Personal comfort system (PCS)
Local heating
Corrective power (CP)

A B S T R A C T

Personal Comfort Systems (PCSs) create a localized comfort situation satisfying individual needs. These devices have low power consumption, as they focus on local environment and thus reduce the energy consumption of main HVAC systems by extending ambient control setpoint ranges. This study focuses on assessing a new type of PCS: a warming desk. It uses the two most efficient and effective means of heat transfer for warming a person: conduction (hands) and radiation (lower and upper body parts facing the table). Two different desks were tested, both simultaneously heating upward and downward with different surface temperatures, one with a higher temperature downward and one with a higher temperature upward. The desks were tested by 30 subjects, inside a climatic chamber, kept at 17 °C air temperature. Both desks are capable of generating good overall (whole-body) comfort and thermal sensation, even leaning towards a slightly warm one for someone. Moreover, results showed that PCS based on direct contact with the skin surface temperature should be kept below 36°, while the surface warming by radiation can reach higher temperatures: personal control of power is critical, as not everyone preferred the same operative temperature. The PCS can "correct" the ambient temperature toward the neutral thermal sensation by about 7K, creating improved thermal comfort compared to centralized HVAC. In its current design, the heating surface required 170W, significantly lower than 500/1500W of a common portable electric heater. It is expected that in an optimized design, the power consumption could be reduced further to 30/40W.

1. Introduction

The mindful use of energy and the reduction of energy waste are important topics, made even more stringent in recent years [1,2]. European policy [3] pushes towards introducing qualitative indices to evaluate building envelopes and HVAC services (heating, ventilation, and air conditioning), focused on reducing energy consumption. Achieving this reduction whilst still improving thermal comfort represents the most important challenge in today's building industry [4].

HVACs are commonly used to create comfortable environments providing a uniform temperature throughout the space. Albeit widely used, people still often complain due to thermal discomfort [5,6]. Moreover, inadequate attention is paid to reducing energy waste [7,8].

Thermal comfort is one factor of Indoor Environmental Quality (IEQ) [9], the most influential in space perception and the predominant on energy consumption [10]. Moreover, thermal comfort is crucial in workplaces, where not only personal well-being increases productivity [11,12], but also currently thermal dissatisfaction accounts for the greatest component of a space's dissatisfaction [13,14].

Buildings do not meet the regulations' modest goal of having no more than 20% unsatisfied occupants, primarily due to individual differences, building over-conditioning, and occupants' inability to adjust the environment individually to meet their personal needs [15]. Existing systems tend to create uniform conditions, which, however, does not create the same thermal sensation in everyone.

Personal differences such as sex, age, clothing, and activity make achieving a shared perception of comfort difficult [16,17]. Moreover, people have a personal capacity to thermoregulate themselves, which

* Corresponding author. University of Pisa, Pisa, Italy.
E-mail address: roberto.rugani@phd.unipi.it (R. Rugani).

https://doi.org/10.1016/j.buildenv.2023.110787
Received 26 April 2023; Received in revised form 13 July 2023; Accepted 29 August 2023
Available online 30 August 2023

differs for every individual [18]. As a result, setting the thermal comfort target to neutrality cannot meet individual preferences [19,20].

This context led many researchers to develop models and systems aimed at meeting personal needs, such as Personal Comfort Systems (PCSs). They are defined as systems that heat and cool individuals without affecting the environments of surrounding occupants [21]. PCS targets the conditioning of only the "personal" microclimate rather than the volume of the entire building, in contrast to traditional HVAC systems [22]. PCSs can be used in several environments and can be clustered and defined according to the combinations of the 3 main services they provide: heating, cooling, or ventilation [23,24].

Thermal sensation and comfort for local body parts varies greatly and affects differently the thermal sensation and comfort perceived by the whole body [21,25]. In a cool environment, hands and feet feel colder than other body parts, representing the main sources of discomfort [26,27]. Moreover, neutral sensation in a uniform environment reaches the rating of "comfortable" but cannot reach the rating of 'very comfortable', which can only be achieved in asymmetric or transient environment conditions [21], often created by PCSs.

PCSs provide a series of benefits to the indoor environment, like ensuring comfort conditions [28–30] and reducing energy consumption [31–34]. PCSs are designed as auxiliaries to main HVAC systems, which can be run to keep the room ambient temperature lower in winter or higher in summer. Indeed, PCS can provide comfortable conditions with environmental temperatures down to 15 °C [4]. Hoyt et al. found a savings of heating energy of 34% just decreasing the HVAC setpoint from 21.1 °C to 20 °C [35,36].

Adjustable PCSs can increase the individuals' thermal comfort, by easily exploit alliesthesia, the pleasurable sensation following an intentional correction of thermal conditions [37,38]. Overall, personal control provides several benefits, both in terms of satisfaction with the thermal environment and in terms of energy savings [27]. These benefits are made even more prominent by the current workplace scenario, where the COVID-19 pandemic enabled and encouraged remote working, leaving many offices understaffed. The direct consequence was seen in the wasted energy needed to air-condition entire offices where most desks remained empty [39]. PCS could provide control of local worker desks while the primary HVAC system works with a wider setpoint range, with a drastic reduction in energy consumption [40]. With the current energy crisis and consequent increase in energy prices [41], PCSs can indeed represent a valuable alternative for many businesses and households. Despite these benefits, the technological solutions for the implementation of PCSs are still being researched, also using innovative meta-analysis comparative strategies [24], to identify the most effective.

For the predictive assessment of users' thermal comfort produced by PCSs, several studies used the Predicted Mean Vote (PMV), which is a numerical index defined as the rating of an average person in relation to uniform thermal environment conditions. Despite PMV being the most used thermal comfort index, included in thermal comfort standards [42,43], there are many disputes about its performance and accuracy [20,44–46], particularly, whether PMV is applicable to PCSs as they do not create uniform thermal environments.

The present study aims to address two research gaps, Firstly, it focuses on analyzing the performance of a technological solution for implementing a PCS. Secondly, it aims to evaluate the accuracy of the Predicted Mean Vote (PMV) in predicting thermal comfort conditions for individuals utilizing the realized PCS. This study contributes to filling these gaps by conducting an experimental analysis of a novel PCS specifically designed for heating, which includes an electric surface embedded within a desk. The PCS operates using the two most efficient and effective ways to warm a person [47], conduction on the hands and radiation on both the lower and upper body, especially the torso and head. Typically, PCSs are designed by exploiting only one type of heat transfer, such as i) conduction in heating chairs or ii) convection in fans with integrated electric heating elements, or iii) radiation for the heating surfaces (floor, ceiling, and so on). This study is among those that aim to combine two types of heat transfer [35,48–51], conduction and radiation, to increase the efficiency in creating the best thermal comfort conditions efficiently. PCSs equipped with multiple-heat transfer mechanisms exhibit a more significant impact in enhancing thermal sensation and comfort and bring substantial benefits [24]. These systems specifically target a larger body surface area while maintaining a lower heating intensity. Rawal et al.'s review indicates that out of 141 research studies on PCS, only 56 considered local thermal variables. Furthermore, the most extensively studied PCS categories are 'Ventilation' and 'Cooling with Ventilation'. Notably, over half of the studies concentrated on devices utilizing convective heat transfer for thermal comfort, highlighting conduction and radiation as significant areas that remain underexplored [23].

Thirty people were asked to evaluate two different desks inside a climate chamber set at an air temperature of 17 °C. Moreover, environmental parameters were measured, and personal thermal sensations were compared with calculated PMV values, to understand the applicability of this methodology in predicting PCS efficacy.

2. Method

2.1. Overview

The aim of the study is to test the prototype of a radiant-conductive heating desk. This study builds upon previous research, through which the new PCS was simulated [40], and further studied and optimized [52]. Initial investigation showed the benefits of the desk in terms of user-perceived comfort and consequent energy savings by keeping the main room in a less conditioned state and managing the local microclimate as a "personal bubble" [40]. The second step envisaged the prototyping of the Loop Heat Desk, a hydronic radiant desk. An innovative system such as a Loop Heat Pipe passively circulates the heating fluid within the pipes [53]. Despite the different shapes and technology, CFD simulations demonstrated the efficiency of the system in recreating the users' local thermal comfort, evaluated using the PMV calculations [52].

The current study involved the first user tests of a radiant-conductive prototype. Commercially available infrared electric desks were selected and installed inside a climatic chamber at the University of Brighton (UK). The desk heats both top and bottom surfaces to warm the upper and lower body parts. In particular, forearm and hands are heated by conduction, typically having direct contact with the table surface; other body parts with optimal view factor toward the desk are heated by radiation. By flipping the table surface upside down, the same desk provides different top and bottom surface temperatures, thanks to the reflective insulation layer in the internal structure (Fig. 2).

The tests with human subject were carried out in the climatic chamber, with two heating desks at different surface temperatures. The climatic chamber was in a less conditioned space regime, i.e., at 17 °C air temperature. This choice stems from the previous analysis, where comfortable conditions could be provided with temperatures as low as 17 °C [40,52].

The subjects' feedback was collected and analyzed, as well as data from probes measurements.

2.2. PCS design

The desk is warmed by infrared electrical technology. The heating system is embedded in the wood, covering almost the entire horizontal surface (Fig. 1). The desk is equipped with an on/off switch allowing the user to control the functioning of the desk.

The desk is designed with a reflective insulation layer above the infrared heat source (Fig. 2), which created two different surface temperatures above and under the desk. Therefore, the two workstations were set up by flipping one desk upside down (Fig. 3).

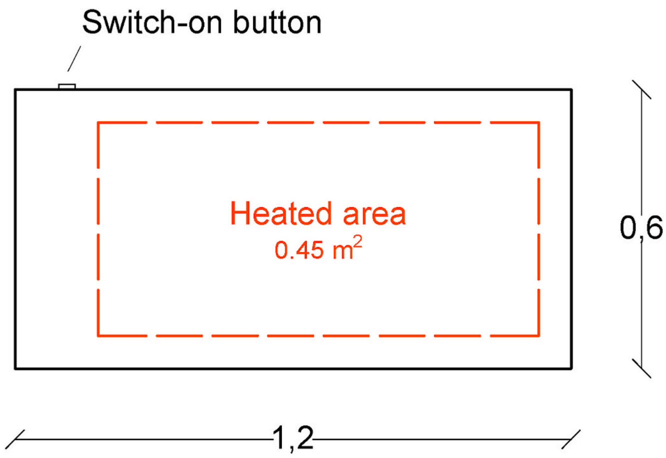

Fig. 1. Desk plan with heating surface identification (in meters).

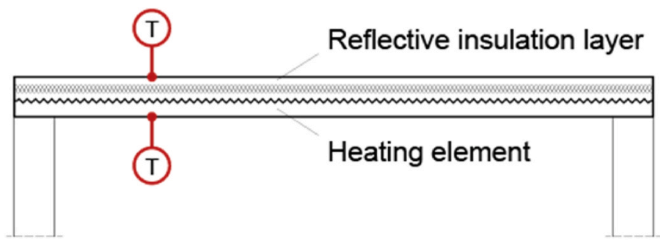

Fig. 2. Desk cross-section, with the indication of the surfaces on which temperatures were measured and the elements that compose the layers.

- desk n°1, regularly oriented, with 30 °C above and 40 °C below;
- desk n°2, flipped, with 36 °C above and 30 °C below.

Temperatures uniformity on the upper and lower table surfaces were checked in two steps.

- first, temperature surface homogeneity was measured with 8 T-type thermocouples placed uniformly on the upper surface of the table (Fig. 4);
- second, the temperatures of the top and bottom surfaces were measured with 8 T-type thermocouples, 5 placed on the top and 3 on the bottom of the desk.

A Variac was used to modulate the heating power and set the designed surface temperatures, which were obtained by delivering 170 W to each desk. The lower surface temperature of desk 1 is higher than the top surface temperature of desk 2 (flipped case). Despite the desks being identical, different temperatures are given by the different volumes of air present above and below the desk. A similar phenomenon does not appear at the upper surface temperatures of desk 1 and the lower surface temperatures of desk 2, which are affected by the reflective insulation.

2.3. Subjects

Thirty volunteers (10 females and 20 males) participated in the experiment. The numbers of subjects under each age group are presented in (Fig. 5). Each participant lived in the south of England, in the East Sussex area, where the weather tends to be cold and rainy. All subjects were volunteers.

Subjects were required to attend without prior alcohol or hot beverage intake, without physical activity and fasting for at least 2 h. All participants were asked to dress as they would normally for a workday. All clothing data were collected through a questionnaire. The clothing

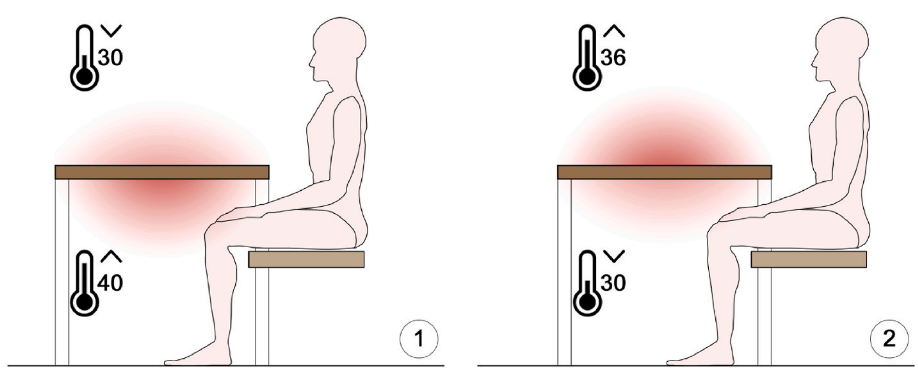

Fig. 3. Schematic view of the workstations, desk 1 and desk 2, with the different superficial temperatures below and above the desks.

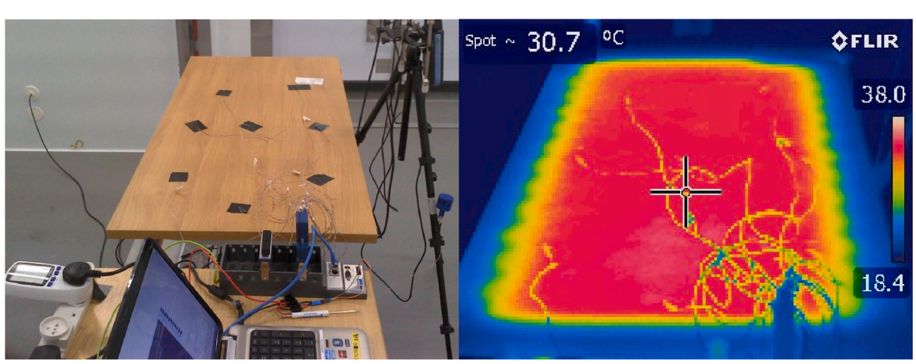

Fig. 4. Normal and thermal cameras same perspective framing of the heating desk during the thermocouples tests in the climatic chamber.

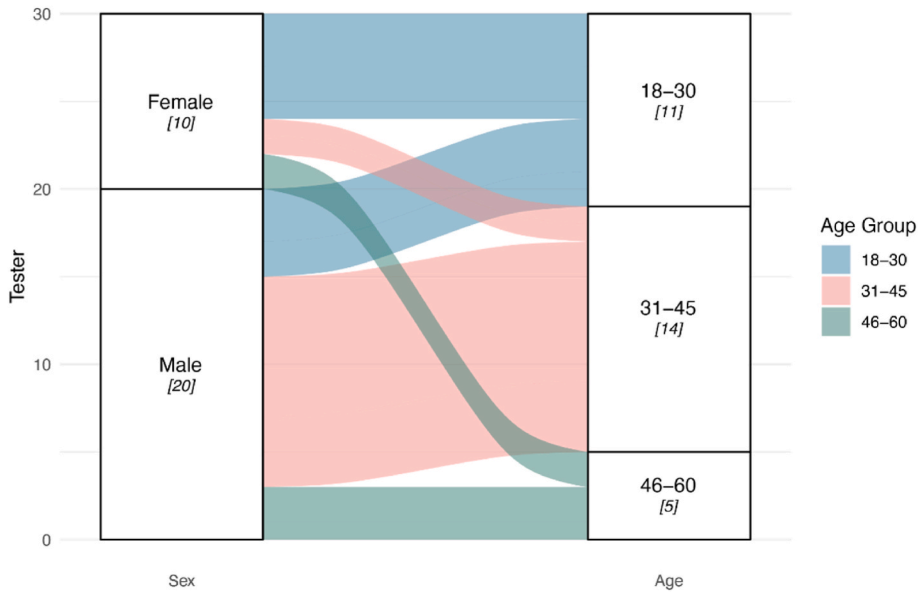

Fig. 5. Subjects' information: breakdown between sex and age group, indicating the number of people in each box.

insulation (I_{clo}) was calculated using equation (1) [54]:

$$I_{cl} = 0.835 \bullet \sum_i I_{clu,i} + 0.161 \quad (1)$$

where $I_{clu,i}$ is the effective insulation of garment i, and I_{cl} is the insulation for the entire ensemble. The median clo value was 0.59 ± 0.12, such as that imposed by Tang et al. [55] during PCSs testing. According to the ANOVA test, there are no significant differences between the male and female clo ($p > 0.175$), and between the clothes of different age groups ($p > 0.5$).

The experiment was conducted over three days at the end of May, during which the climate and temperature conditions remained constant.

2.4. Experimental schedule and conditions

The tests were conducted in a climatic environmental chamber at the University of Brighton (Figs. 7 and 8). The chamber dimension is 5 m (length), 4 m (width), and 3.2/3.6 m (height). The space is set with two test stations, with desk 1 and desk 2 (flipped). The HVAC system is in the smaller separate side of the room and can control temperature and humidity, with ±0.1 °C and ±2% RH accuracy.

Experimental conditions were set at 17 ± 0.1 °C air temperature with relative humidity at 50 ± 2%. The air velocity was always below 0.1 m/s.

The test schedule is shown in Fig. 6. Each person was kept for 15 min to acclimatize in an adjacent room, without HVAC, prior to testing. During this time, participants were informed of the possible risks and signed a written consent. Following, once people entered the room they were randomly placed at the 1st or 2nd desk. The two desks were switched on in advance in order to reach steady surface temperatures. They were placed at a classic office distance from each other (≅ 1.2 m) so that one's heating would not affect the other (Fig. 7). After 20 min, after filling in the survey, subjects were moved to the other desk and repeated the procedure.

It was a blind experiment and as such people were informed that the desks were heated, but they did not know the differences. During the 40 min at the desks, they could talk to each other, study, or conduct office activities, but they were not allowed to exchange their opinions about the heated desks.

The experiment protocol was reviewed and approved by the Cross-School Research Ethics Committee of the University of Brighton (Ref: 2022–10139).

2.5. Survey questions

The thermal comfort surveys were compiled after spending 20 min at each desk. They consisted of four parts: a first one with generalities such

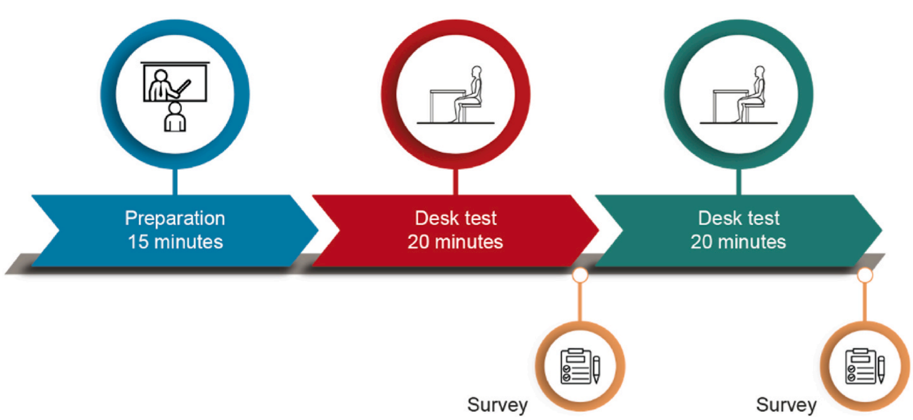

Fig. 6. Experimental procedure (timeline).

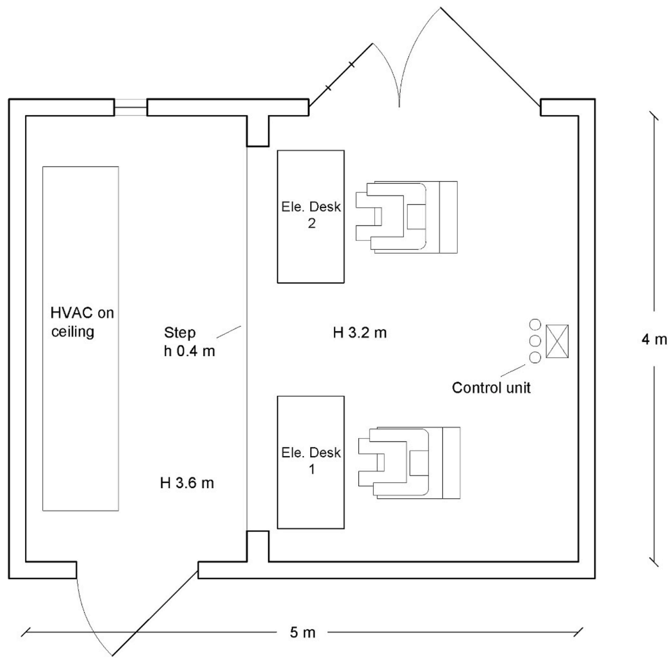

Fig. 7. Architectural plan of the climatic chamber with the configuration used during the tests with people.

Fig. 8. Inside of the climatic chamber set up for the tests with people.

as gender, age, and clothing; a second and third identical one, with the thermal control ratings of the two desks, respectively. In particular, questions were about global thermal comfort (whole-body), thermal sensation, thermal preference, and local thermal sensation for different body parts: head, torso, arms, hands, legs, ankles, and feet. The full scale of available responses is shown in Table 1. Moreover, for each desk, subjects were asked if they would have preferred to be able to control desk temperatures.

Table 1
Thermal evaluation scales for the surveys.

Scale	Global thermal comfort	Thermal sensation (global/ local)	Thermal preference
3	Excellent	Very hot	Much cooler
2	Very good	Warm	Cooler
1	Good	Slightly warm	Slightly cooler
0	Normal	Neutral	Without change
−1	Bad	Slightly cool	Slightly warmer
−2	Very bad	Cold	Warmer
−3	Terrible	Very cold	Much warmer

In the last section, a desk comparison was prompted asking subjects if they found differences between the two desks and if so, which one was more comfortable, and why. This question was asked at the end of the entire test.

2.6. Probes test for the ambient conditions and calculated PMV (Predicted Mean Vote)

The same test conditions conducted with people were repeated using probes (Fig. 9). The time needed to reach the designed steady-state temperatures was measured, and the following data were recorded every 30 s.

- air temperature at face height (1.10 m), torso height (0.60 m), and ankle height (0.10 m);
- floor temperature;
- desk superficial temperatures (8 points);
- air velocity;
- air humidity.

The Deltaohm HD32.3 data logger was used, with a thermo-hygrometer, a globe thermometer, and an omnidirectional hot wire anemometer. Moreover, 10 T-type thermocouples were used, and data logged via a NI cRIO. Detailed probes characteristics are shown in Table 2. The probes were placed in front of the desk (Fig. 9), simulating the position of a real desk user.

The model developed by Fanger [56] was used to assess thermal comfort based on the ambient measured data, which calculates as output the Predicted Mean Vote (PMV). The inputs of the models are four environmental parameters (air temperature, mean radiant temperature, relative humidity, and air velocity), obtained with the Deltaohm probes, and two individual parameters (clothing insulation and metabolic rate). Clothing insulation data were collected through the survey, as mentioned in section 2.3. PMV results will be variable depending on the specific CLOs of the participants. The metabolic rate was set to 1.2, according to the ASHRAE Standard 55 [42] level for office work.

Consequently, the relationship between PMV and the Thermal Sensation Vote (TSV) collected from the survey was studied, to assess the applicability of Fanger's method in predicting the thermal sensation provided by PCSs.

Furthermore, we investigated whether desks caused discomfort due to vertical air temperature differences between head and ankles [54,57] (2):

$$PD = 100 / 1 + \exp\left(5.76 - 0.856 \bullet \Delta t_{a,v}\right) \tag{2}$$

where PD is the Percentage Dissatisfied and Δt are the temperature differences between head and ankles in each case. The comfortable vertical temperature gradient between head and feet limit is prescribed as 3 °C/m by ASHRAE 55 [42] and ISO 7730 [43], though Liu et al. found that it changes with thermal sensation votes and could be increased to 5 °C/m when the subject is thermally neutral [58].

2.7. PCS efficiency evaluation

A PCS system offers both thermal comfort and energy benefits. Indices were created to evaluate the contribution of PCSs and to be able to compare different systems with each other.

The Corrective Power (CP) [32] evaluates the comfort contribution by Personal Comfort Systems, quantifying how much a PCS can correct the room temperature to recreate the neutral sensation. It is defined as the difference between two ambient temperatures, one with PCS ($T_{n,PCS}$) and one without (T_n) at which the same thermal sensation is achieved

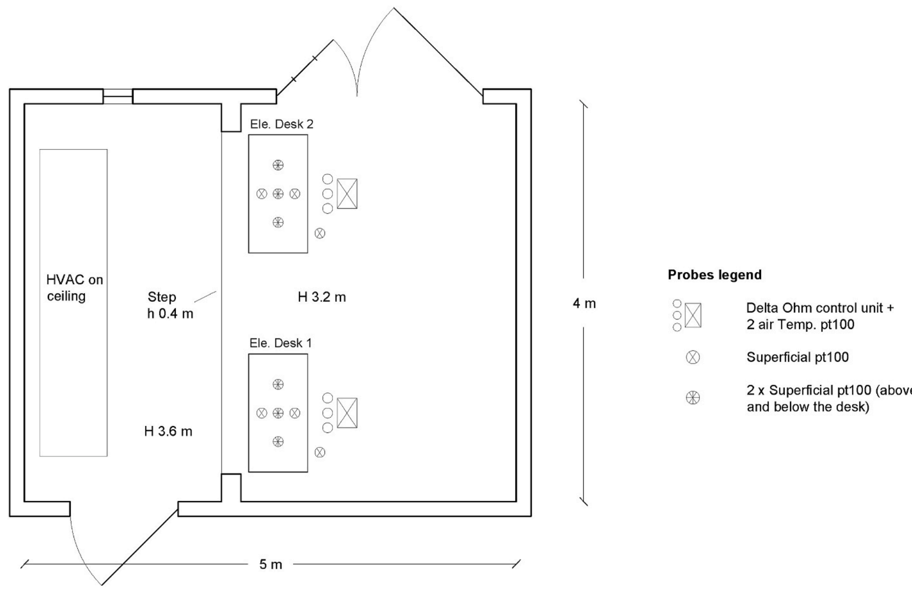

Fig. 9. Architectural plan of the climatic chamber with the configuration used during the tests with probes.

Table 2
Thermal evaluation scales for the surveys.

Probes	Variables	Resolution	Calibration
Pt100 - RH	T and RH	±0.1 °C/± 0.1%RH	*Manufacturer*
Globe thermometer	Radiant T	±0.1 °C	*Manufacturer*
Omnidirectional hot wire	Air speed	±0.01 m/s	*Manufacturer*
T-type thermocouple	T	±0.5 °C	Temperature bath

(3). The unit is the temperature degree.

$$CP = T_{n,PCS} - T_n \tag{3}$$

CP-related energy consumption assessment in PCSs studies is based on two indices. The Corrective Energy & Power (CEP) [59] quantifies the energy required by PCSs for each CP degree achieved. It is defined as the ratio of electric power ($\dot{Q}$) to the absolute value of the CP (4).

$$CEP = \dot{Q}/|CP| \tag{4}$$

The Coefficient of Performance (COP) [35] stands for the efficiency of the PCS, showing the CPs obtained per unit of energy consumption. It is defined as the ratio of the absolute value of the CP to the electric power ($\dot{Q}$) (5).

$$COP = |CP|/\dot{Q} \tag{5}$$

In the present study, the COP index will be used to show the efficiency of the PCSs.

2.8. Statistical analysis

The statistical analysis was performed using the R software. The sample distribution was not significantly different from a normal distribution. The correlation between subjective features and comfort votes was assessed by Spearman's rank correlation coefficient. The significant differences in comfort votes between desks were assessed by the Analysis of variance (ANOVA); the probability value threshold for statistical significance was set at $p = 0.05$. The questionnaire's experimental results are shown as the mean ± the Standard Deviation (SD).

3. Results

3.1. Overall thermal comfort

Fig. 10 shows the effect of the two desks on overall thermal comfort (whole-body). The Global thermal Comfort Vote (GCV) for desk 1 is 1.17 ± 0.87 (good), which is slightly higher than the 0.83 ± 1.05 (good) of desk 2, but still significantly different ($p = 0.04$).

Fig. 11 highlights votes according to age group and sex. Men perceive a slightly less comfortable than women at both desk 1 ($p = 0.78$) and desk 2 ($p = 0.29$), although this difference is not significant, but still with average ratings between good and very good. The age group breakdown does not result in significant differences ($p > 0.3$), except for women in group 46–60 who drop desk 2 perceptions to a 'normal' grade.

3.2. Overall thermal sensation

The overall thermal sensation votes (whole-body) for the two desks are shown in Fig. 12. The TSV for desk 1 (0.23 ± 1.04) is significantly lower than those of desk 2 (1.13 ± 1.04) ($p < 0.001$), so indicating a move from a neutral to a slightly warm condition.

No noticeable significant differences in the thermal sensation ratings are shown in Fig. 13, with a TSV of 0.3 ± 0.98 for men and 0.1 ± 1.16 for women in desk 1 ($p = 0.94$) and 1.25 ± 1.02 for men and 0.9 ± 1.07 for women in the desk 2 ($p = 0.92$). The same observations apply to the

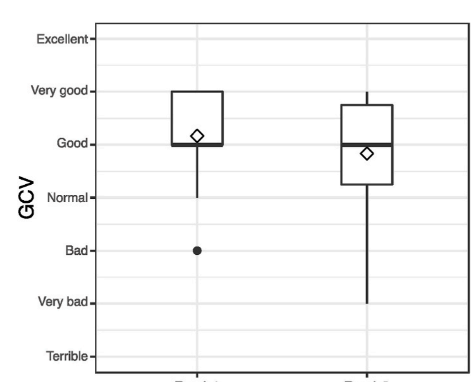

Fig. 10. Global comfort votes for Desk 1 and Desk 2.

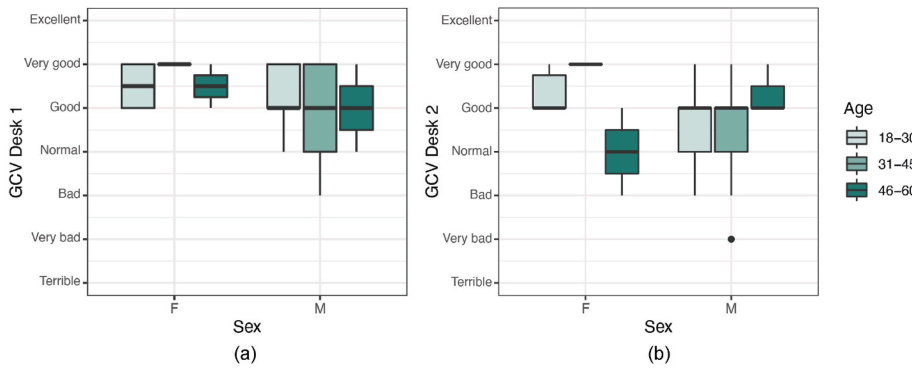

Fig. 11. Global comfort votes for Desk 1 (a) and Desk 2 (b) as a function of age and sex.

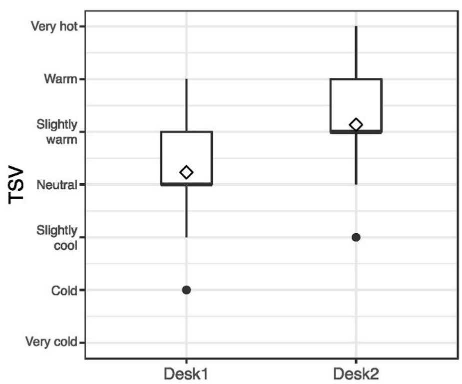

Fig. 12. Thermal sensation votes for Desk 1 and Desk 2.

age group results (p > 0.3).

3.3. *Thermal preference*

The desired changes in the thermal environment are shown in Fig. 14. Although at ambient temperature as low as 17 °C, desk 2 produces a sense of warmth that results in a demand for a slightly cooler environment (0.47 ± 0.93). Desk 1 significantly produces the opposite request ($p < 0.001$), with people asking for no changes, other than preferring a slightly warmer environment (−0.27 ± 0.82).

The Thermal Preference Vote (TPV) and the GCV highlight a similar trend, with people in the 46–60 age group preferring cooler conditions, especially for desk 2 (Fig. 15). The TPV of desk 1 is −0.25 ± 0.91 for men and −0.3 ± 0.66 for women ($p = 0.19$), and those of desk 2 is + 0.6 ± 0.94 for men and +0.2 ± 0.89 for women ($p = 0.37$). Except for the case already highlighted, all other groups report no significant differences ($p > 0.3$).

The percentage of total votes in Fig. 16 leans toward a heat overload situation at desk 2 and a slighter demand for heat compensation at desk 1. Indeed, 43% of desk 2 users would prefer a cooler environment, compared with 20% of desk 1. On the other hand, 43% at desk 1 and 13% at desk 2 would like a warmer environment. These thermal preference votes match the thermal sensation votes (Fig. 12) where people felt warmer at desk 2 than at desk 1.

3.4. *Personal control*

The prototypes lacked the capability of being able to independently control the power of the desk, allowing only the on/off function. Therefore, users were asked whether they preferred to be able to control the temperature themselves, to improve their thermal comfort sensation: the results in Table 3 show a clear path in the direction of “yes”.

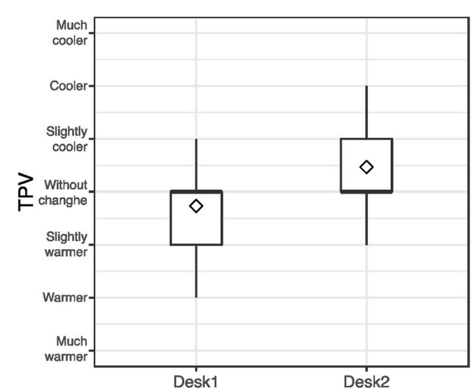

Fig. 14. Thermal preference votes for Desk 1 and Desk 2.

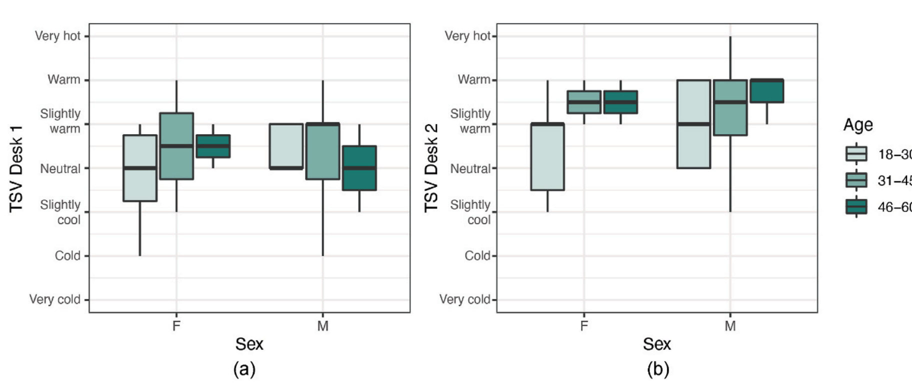

Fig. 13. Thermal sensation votes for Desk 1 (a) and Desk 2 (b) as a function of age and sex.

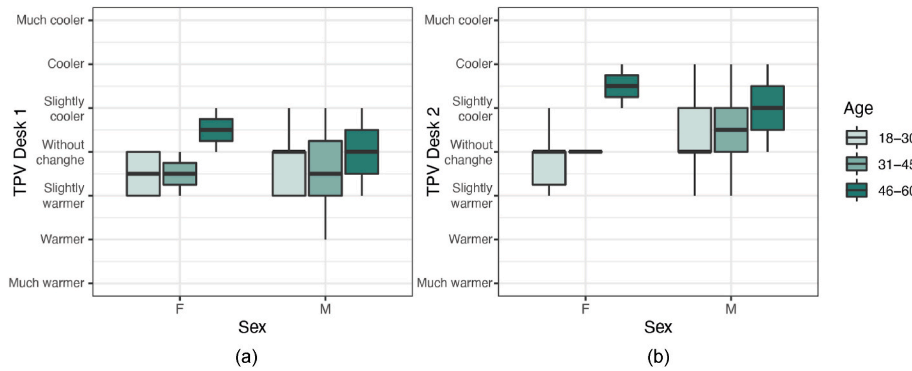

Fig. 15. Thermal preference votes for Desk 1 (a) and Desk 2 (b) as a function of age and sex.

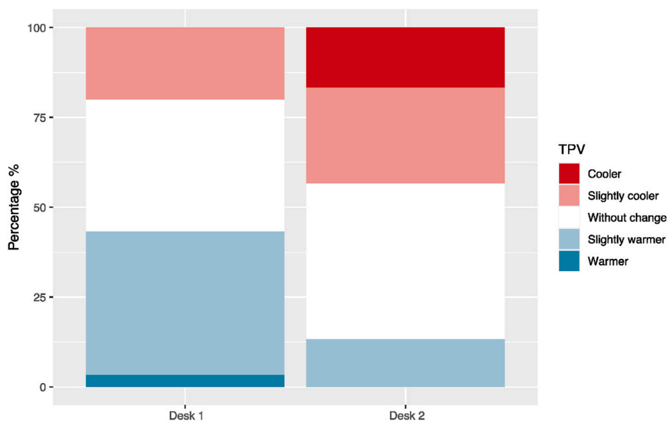

Fig. 16. Thermal preference votes for Desk 1 and Desk 2, shown as a percentage.

Table 3
Personal control votes, desire for self-control.

	Desk 1	Desk 2
Yes	27	25
No	3	5

3.5. Local thermal sensation

Local body sensation varies dramatically in the two configurations, as expected. Fig. 17 shows all votes distribution, placing side by side the two desks' results for each body part, facilitating the comparison.

Each perceived TSV in front of the two desks is significantly different ($p < 0.01$), except for the torso (although it does not deviate much from the set cut-off percentage, $p = 0.08$) and legs ($p = 0.88$).

Fig. 18 shows thermal sensation using color gradients, starting from cold (light blue), to neutral sensation (white), until warm (red). Desk 1, the one that heats more the lower body parts, creates a more comfortable thermal sensation, with a slightly warming feeling toward the body parts next to the heating surface. Desk 2, which warms more the upper body parts, provides a warm feeling in the arms and hands thereby creating an imbalance with the body parts below the desk, which feel slightly cold.

3.6. Desk preference

In the last part of the survey, after the subject finished the two tests with the two desks, people were asked which desk they preferred. Not everyone made the same choice: 19 people (63%) preferred desk 1, and 11 people (37%) desk 2 (Fig. 19).

No clear differences emerged between the preference of males and females ($p = 0.08$), however, a slightly more noticeable gap appeared between the different age groups ($p > 0.20$). Desk 1 is preferred by 55% of the 18–30 group, 64% of the 31–45 group, and 80% of the 46–60 group.

Fig. 20 shows that there is no clear distinction between groups and desk preferences. All users perceived clear differences between the two heating desks, albeit with a random selection of their favorite one.

3.7. Personal open answers

The most frequent complaint from the subjects was about the surface temperature of desk 2 being too high (36 °C), with comments such as: "*Upper side of the desk 2 too hot*", "*Desk 2 is too hot to the touch and legs still feel slightly cold*", "*2 is too hot. 1 appears to have the heat zones right where I need*".

However, several people preferred desk 2 because of the greater warmth provided: "*Desk 2 feels slightly warmer and I find it warms whole body rather than just arms*", "*I felt slightly cold at desk 1, desk* 2 had *a warmer environment*".

At the same time, preferences toward desk 2 were also directed to the more uniform perception of warmth thermal sensation: "*It felt warmer.*

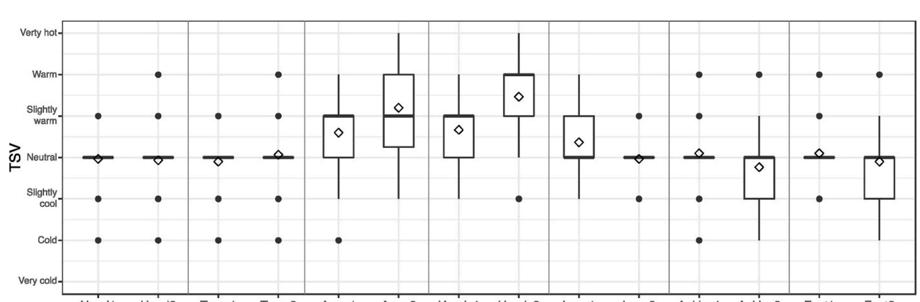

Fig. 17. Local thermal sensation votes for head, torso, arms, hands, legs, ankles, and feet, divided for Desk 1 and Desk 2.

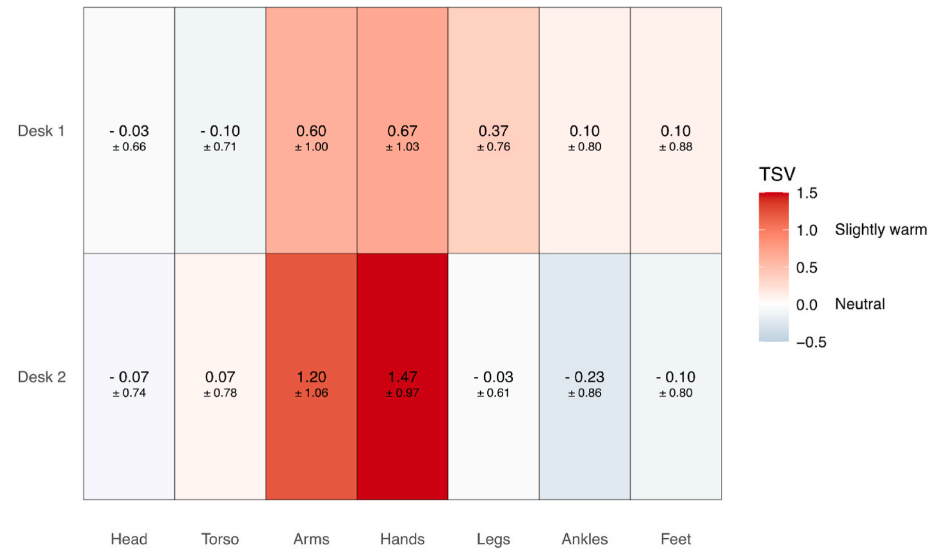

Fig. 18. Local thermal sensation votes mean for head, torso, arms, hands, legs, ankles, and feet, divided for Desk 1 and Desk 2.

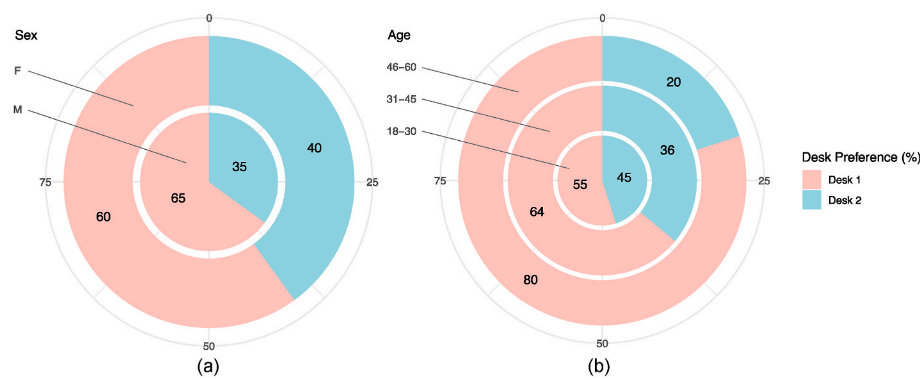

Fig. 19. Desk preference, divided for sex (a) and age (b), and displayed as percentage.

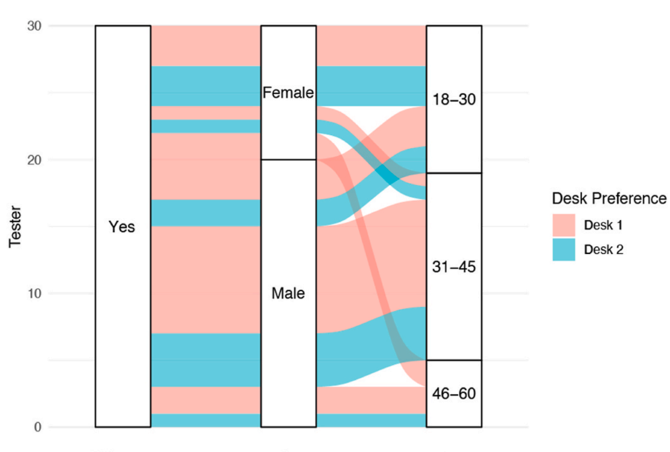

Fig. 20. Desk preference, relationship among those who perceived differences, sex, and age.

The heat seemed to spread to my torso more effectively", "*Although I feel desk 2 is too hot/warm, I feel overall better and my body is warm in a more homogeneous fashion*".

The preferences toward desk 1 are greater, as already highlighted, and the main feedbacks are.

- Lower upper surface temperature: "*D2 temperature is maybe too high to work with the desk*", "*The temperature on 1 feels optimal for my body*".
- Pleasant overall thermal sensation in warming the lower body parts: "*I preferred the warm more on my legs, with some residual heat on top (Desk 1)*", "*D1 legs are warmer*", "*Desk 1 tended to warm up my legs which I found more comfortable*".

3.8. Probes results

PMV values are calculated with environmental data measured by the DeltaOhm data logger and their variability is due to the variation in each participant's Clo level (Fig. 21). The probes are in front of the desk, as real desk user.

The assessment of radiant desks by means of PMV would seem to provide little benefit to thermal comfort, moving from a cold to a slightly cool sensation (Fig. 21). Actually, the results of the user test showed quite different thermal sensations. Fig. 22 shows the differences between PMV and TSV on each desk.

Fig. 22 shows a great variation between PMV and TSV for each desk. The TSV values are those collected with the surveys, already shown in Fig. 12. When PMV predicted slightly cool thermal votes (-1.3 ± 0.35 for Desk 1 and -1.09 ± 0.33 for Desk 2), the real thermal sensations are averaged on the neutral rating for desk 1 (0.23 ± 1.04) and slightly warm for desk 2 (1.13 ± 1.04).

A linear regression on the ability of the PMV to predict TSV showed an R^2 of 0.004 and a Mean Absolute Error (MAE) of 0.83 for Desk 1, and

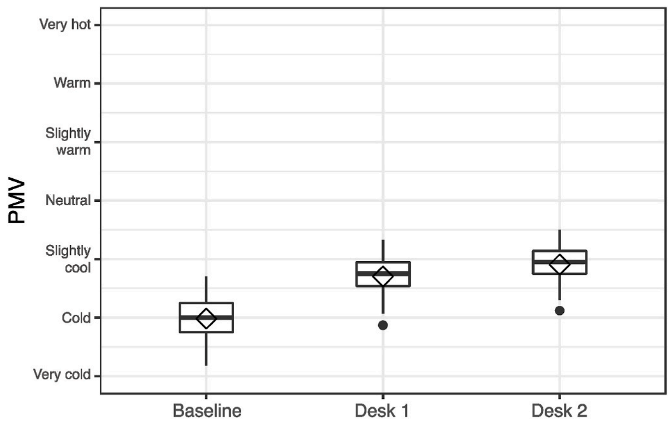

Fig. 21. PMV for the baseline scenario, without a heating desk, desk 1, and desk 2.

an R^2 of 0.017 and a MAE of 0.80 for Desk 2. Cheung et al. found similar results ($R^2 = 0.08$ and a MAE = 1.02) in comparing a larger sample of PMV and TSV data contained in the ASHRAE Global Thermal Comfort Database II [44].

Since the location of the probes was at the head height (1.10 m), the PMV was compared with the local head TSV (Fig. 23).

The local TSV for heads is −0.03 ± 0.66 (neutral) for desk 1 and -0.07 ± 0.74 (neutral) for desk 2, still different from PMV which predicts a slightly cool environment.

The model is somewhat more accurate than the previous one, with $R^2 = 0.012$ and MAE = 0.33 for desk 1 and $R^2 = 0.014$ and MAE = 0.40 for desk 2, yet still unacceptable.

Vertical temperature gradient did not contribute to discomfort: there were no major temperature differences between the ankles and the head, as the surface heats in both directions. The PD value due to temperature stratification is 0.36 for desk 1 and 0.62 for desk 2, with vertical differences below 1 °C.

3.9. CP and COP of the PCS

CP is calculated for both desks based on subjects' thermal sensations. Desk 1 creates a TSV of 0.23 ± 1.04, so in the neutral range (−0.5/ +0.5). No tests were carried out to find the corresponding temperature that recreates neutral sensation, without PCS. But since the experiment was performed in a stationary environment, it is possible to assume the temperature corresponding to neutral sensation using PMV, which was found to be 24 °C. Therefore, CP_1 for desk 1 is 7K.

Desk 2 creates a TSV of 1.13 ± 1.04 (slightly warm), which is warmer than the neutral feeling. It is not possible to know the ambient temperature at which the desk is able to recreate the neutral sensation, since no tests were performed with the climate chamber air temperature below 17 °C. It can only be assumed that the CP is greater than that of desk 1, so $CP_2 > 7K$.

A Variac was used to set the electric power in order to obtain the desired desk surface temperature. Each desk absorbs 170W of electrical power. Hence, the COP_1 is 0.04, and $COP_2 > 0.04$.

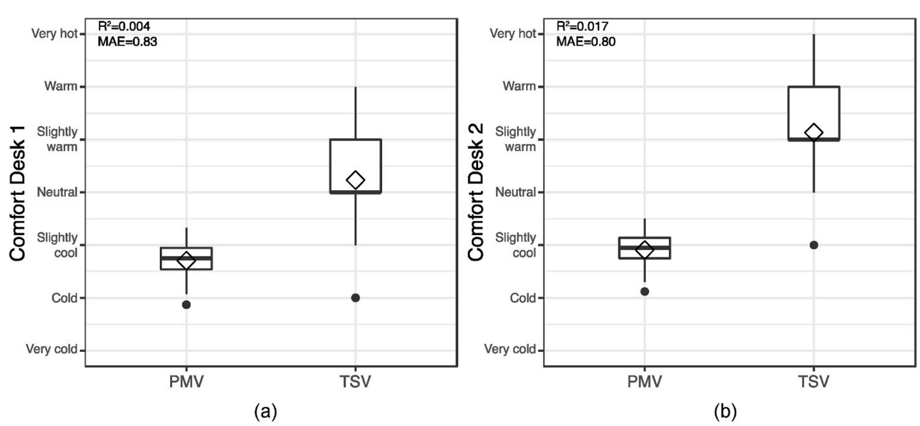

Fig. 22. PMV and overall thermal sensation votes for desk 1 (a) and desk 2 (b). Indication of coefficient of determination R^2 and mean absolute error (MAE).

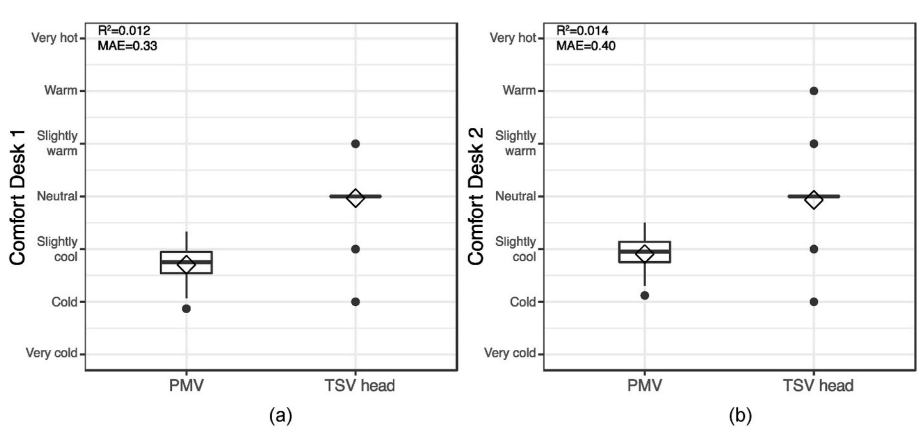

Fig. 23. PMV and local face thermal sensation votes for desk 1 (a) and desk 2 (b). Indication of coefficient of determination R^2 and mean absolute error MAE.

4. Discussions

4.1. Overall comfort

The two desks met expectations, creating a comfortable environment with a low room air temperature (17 °C instead of the usual 21 °C to maintain a good level of average comfort[1]); desk 2 even provides a slightly "too warm" feeling.

Generally, users perceived a comfortable environment, rating it as "good" ("+1″ value on the 7-point scale, see Table 1).

Whole-body TSV follows the trend of GCV, with people tending to rate desk number 1 with values next to the neutral sensation, deeming desk 2 too warm. Indeed, the mean TSV for desk 2 is 1 point higher, which is a considerably significant difference ($p < 0.001$), even with a standard deviation of 1.04. The higher temperature toward the upper parts of the body causes a thermal sensation of being too warm for most of those tested. In personal open-ended answers, this point was often emphasized.

It is interesting, although the surface temperatures for desk 2 (30 °C ↓, 36 °C ↑) are lower than the surface temperatures for desk 1 (40 °C ↓, 30 °C ↑), the overall sensation is warmer for desk 2 than desk 1. This result is similar to the local thermal sensation on the whole-body thermal sensation model presented by Zhang et al. [27] where it is shown that in cold or warm environments, local body parts heating or cooling has a dominant effect on the whole-body thermal sensation. This also explains why PCSs work with less energy – they create a bigger effect by focusing on local body parts. It also explains why the subjective votes in PCS conditions are very different from the PMV predictions, as PMV is designed for uniform environments.

However, more people prefer desk 1 to desk 2 in the cold ambient temperature. Based on the subjective surveys, people like to have lower body parts (legs and feet) feel warm. The same findings were also observed by Zhang et al. [27] which show that cool hands and feet discomfort dominate the whole-body discomfort in cool environments. To make PCS work effectively and comfortably for the whole body in cool conditions, the extremities need to be warmed.

The thermal preference rates reflect the GCV and TSV results: users of desk 1 require almost no changes (-0.27 ± 0.82), while on desk 2 people would like to be a little cooler (0.47 ± 0.93), considering the 0 rates as "no changes", −1 "slightly warmer" and +1 "slightly cooler".

Standard deviations are always in the range of 1 point on a scale of 7, so even though the mean values are very close to comfortable situations, not quite all users were in their most comfortable condition. Furthermore, almost everyone would like to control and slightly change the desk temperatures: out of 30 people, 27 for the desk 1 and 25 for the desk 2. People have very personal and dynamic thermal sensations, dictated by the activity preceding the use of PCSs, personal moods, physiological characters, and so on. It is critical to be able to provide the user with the ability to control the power of the PCS and not just the ability to turn it off and on; moreover, this being able to control creates pleasure sensation, the alliesthesia. Thus, the perception of a better environment is by being able to control it. The higher standard deviation further demonstrates that individual difference is big, and personally controlled PCSs have a good potential to provide individual comfort.

Desk's operation was evaluated during tests and by feedback, which confirmed the initial hypothesis that a reduction in the heating surface dimensions would optimize cost and system efficiency while yielding the same thermal comfort. An initial estimate expects a heated area of no more than 0.12 m^2, which is 27% of the current desk heating surface.

Firstly, the top desk might have devices, such as laptops, which would risk overheating and causing damage. Moreover, people tend to always use the same portion of the desk, leaving objects in the remaining empty spaces, which are unnecessarily heated. Therefore, the next step of heating desk optimization should have a smaller heated surface area located in front of the user's position.

For the lower surface of the desk, it would be more energy efficient to place the heating elements in a wider view factor to the lower body parts.

There were no statistically significant differences in voting by males and females, or among the 3 age groups highlighted. Except for a few cases, p-values were often greater than 0.3.

4.2. Local thermal sensation and preference

Local sensations showed that the greatest desk contributions were concentrated on the hands and lower body parts. Moreover, the two desks' contributions were significantly different: the face, arms, hands, and feet thermal sensation votes vary with p-values in the order of 10^{-5}.

The ranges of thermal sensation votes are wide and therefore it was not possible to obtain a clear preference towards one of the two desks. The average values of TSV and GCV suggest that desk 1 performs better than the other. However, this is not always the case, as 37% of users preferred desk 2, justifying the choice with several reasons.

Each PCS should be accessorized with the user's ability to control power. 90% of desk 1's users and 83% of desk 2's users would like to independently and separately control the setpoints of the two heating surfaces. According to the results and the open-ended answer, providing the users the ability to independently control the desk's top and bottom surface temperatures, a rating range near 0 sensations would have been obtained, being this the targeted neutral comfort value.

4.3. PMV vs TSV for PCS

The debate on PMV efficacy in predicting the exact thermal sensation is alight. The Authors wanted to investigate if, through the placement of measurement probes near the PCS, the PMV was able to predict what the user's sensation is likely to be.

Results showed that PMV should not be applied in evaluating the effectiveness of an asymmetric environment created by PCSs, because its prediction accuracy is even lower than when applied to a steady, stationary environment. Part of the reasons is also explained above (under the "Overall comfort" section).

When PMV predicted a slightly cool environment, the real users' thermal sensation was between neutral and slightly warm. Moreover, the stratagem of comparing the PMV with the thermal sensation of the head did not solve the situation, although it did reduce the difference (although the PMV was created as a global index, the probes were placed at the face height of a seated person, 1.10 m). For the two models, R^2 did not go beyond 0.012, with a MAE of 0.33/0.4.

4.4. PCS efficiency

Results showed good desk performance in terms of thermal comfort. On the other hand, energy performance is average but can be optimized.

Table 4 shows the results of other PCS studies performed on similar devices, thus transferring by radiation and conduction. Among others, only the warm barrel has a higher CP than the heating desks, which is very similar to a stove and works only with the radiant contribution.

The energy consumption is influenced by the PCS design. The systems working only through radiation are designed to operate at higher temperatures, which is why consumption far exceeds the average of the other PCSs listed in Table 4.

The power consumption must be compared with the possible reduction in consumption of the main air conditioning system set at a lower temperature. Indeed, a reduction of 3K–18.3 °C saves 32%–73% [36]. From an energy efficiency point of view, PCSs are successful only when coupled with a change in HVAC setpoints, otherwise, they are just

[1] It is to consider that a reduction of 1 °C in an office environment is able to save up to 34% of winter energy load, depending on the volume of the office, external climate, characteristics of walls and windows.

Table 4
Comparison of the CP and COP of radiating and conductive heating PCSs. Update of table proposed by Tang et al. [55].

Research	Device	Air T (°C)	Relative humidity (%)	Clothing insulation (clo)	TSV	CP (K)	Power (W)	COP (K/W)
This study	Desk 1	17	50	0.59	0.23[a]	7	170	0.04
	Desk 2	17	50	0.59	1.13[a]	>7	170	>0.04
Tang et al. [55] 2022	Radiant heater	18	50	0.60	−0.20[a]	7.5	630.1	0.01
	Heating chair	18	50	0.60	0.00[a]	7.5	43	0.17
Wang et al. [60] 2021	Floor heating mat	13 (1.2 met)	40	1.25	−0.7[a]	>2	450	>0.004
		13 (1.45 met)	40	1.25	−0.2[a]	>2	450	>0.004
		13 (1.69 met)	40	1.25	−0.1[a]	>2	450	>0.004
Luo et al. [35] 2018	Heating chair	18	40	0.65		1.25	14	0.09
Yang et al. [61] 2018	Heating chair	14	50	0.95	−0.8[a]	2	<90	>0.02
		16	50	0.95	−0.4[a]	/	<90	/
		18	50	0.95	−0.1[a]	/	<90	/
He et al. [59] 2017	Warm-barrel	9	50	1.00	−0.4[a]	13	165	0.08
		12	50	1.00	−0.1[a]	10	140	0.07
		15	50	1.00	−0.3[a]	7	104	0.07
		18	50	1.00	−0.1[a]	4	50	0.08
Zhang et al. [34] 2015	Radiant footwarmer	18.9	/	/	−0.9[a]	<2.2	21	>0.10

[a] 7-scale thermal sensation
[b] 9-scale thermal sensation
[c] Hypothesis situation, following the results of the present study

an extra load.

COP values are highly variable depending on the type of PCS chosen, its position, and its interaction with the person being warmed. The two desks' indices do not differ much from the average of the other PCSs, but they can be significantly increased with minor modifications.

The current desk power consumption is 170W. A commonly used portable electric heater consumption is around 500/1500W. The comparison is intentionally given with a portable electric heater to provide the maximum ranges of energy efficiency improvement, and because it is the most accessible on the market and therefore the most widely used in cold discomfort situations.

As per user feedback, the desks' heating area needs to be reduced. Power $\dot{Q}$ and heating surface S are directly proportional, so the reduction of S also leads to the reduction of $\dot{Q}$, and consequently to an improvement in the COP index. With a heating surface located exactly in front of the user, for a width of 60 cm and a length of 20 cm, the power required by the desk would drop to 30W, resulting in a COP of 0.23. It is expected that, with this reduction, the CP of desks should remain the same, since the view factors of the heated surfaces do not decrease too much. However, this needs to be further tested.

4.5. Limitations

Due to external constraints, the study was limited in the number of personal questions that could be asked to participants (such as height, weight, BMI). This limitation was overcome by increasing the number of participant and randomizing the selection.

The authors used a 7-point comfort scale that is different from what is considered standard, though used in other studies [55,59,62,63]. The underlying rationale was to conduct a study that could be effectively compared with existing research on similar PCS [55,59].

Finally, it was not possible to conduct a third experiment recreating a homogeneous environment at 17 °C without PCS. This was deemed not necessary as, in a homogeneous environment, it is assumed that the current thermal comfort prediction models are effective in predicting the required comfort results.

5. Conclusions

This paper investigated the heating performance of a new Personal Comfort System, an innovative heated desk. This study was conducted in a climatic chamber set at a temperature of 17 °C, where 30 test subjects evaluated the thermal comfort provided by two desks with different higher and lower temperatures between the top and bottom surfaces. The main findings of this study are summarized as follows.

- Even in a less conditioned space (17 °C), the desks created a neutral comfort environment, heating efficiently hands by conduction and the ankles and face by radiation; in some cases, participants felt even slightly warmer than needed;
- Both local TSV and open-ended feedback showed that hands in contact with a surface at 36° can create discomfort. Hence, direct skin contact-based PCS should keep surface temperature below 36 °C;
- The current PCS has a corrective power of 7K and a COP of 0.04. The consumption of 170 W is still significantly lower than 500/1500W of a common portable electric heater;
- Reducing the heating area to 0.12 m^2 would reduce the consumption to 30W, bringing the COP to 0.23. Further tests are needed to ensure that the same CP is provided;
- Fanger's rational method, thus the PMV index, cannot predict the benefits brought by PCS, and therefore should not be used in asymmetric environments.

Previous studies already demonstrate possible 20–40% energy savings by reducing the centralized heating setpoint of 3K [36,40]. PCS standalone power consumptions are significantly lower when compared to the HVAC energy savings. In addition, in a standard office setup, the desks are not always occupied; PCS can provide more granular temperature control, further reducing energy consumption.

Future developments

Future developments of this study include tests on an improved prototype desk, in which the most important aspects to study are: reducing the heating surface area, varying the locations of the heating areas, and being able to independently control the surface temperatures above and below the desk; the contribution of alliesthesia would further improve the perceived comfort; Finally, tests should be performed in a real office environment with heated desks and in a less conditioned space to measure actual power consumption and savings.

Funding

The research activity was partially funded by the Advanced Engineering Centre of Brighton and the ILO-2 Consortium.

CRediT authorship contribution statement

Roberto Rugani: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Bernagozzi:** Writing – review & editing, Visualization, Validation, Methodology, Data curation, Conceptualization. **Marco Picco:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Giacomo Salvadori:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Conceptualization. **Marco Marengo:** Writing – review & editing, Visualization, Resources, Project administration, Funding acquisition, Conceptualization. **Hui Zhang:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Fabio Fantozzi:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Roberto Rugani reports equipment, drugs, or supplies was provided by Okoform.

Data availability

The data that has been used is confidential.

Acknowledgment

The authors want to acknowledge Okoform for providing the desks tested during the study.

References

[1] A. Allouhi, Y. El Fouih, T. Kousksou, A. Jamil, Y. Zeraouli, Y. Mourad, Energy consumption and efficiency in buildings: current status and future trends, J. Clean. Prod. 109 (2015) 118–130, https://doi.org/10.1016/j.jclepro.2015.05.139.

[2] R.A. Almasri, M.S. Alshitawi, Electricity consumption indicators and energy efficiency in residential buildings in GCC countries: extensive review, Energy Build. 255 (2022), 111664, https://doi.org/10.1016/j.enbuild.2021.111664.

[3] E.U. Buildings, Energy Performance of Buildings Directive, 2020. https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en. (Accessed 21 December 2020).

[4] M. Veselý, W. Zeiler, Personalized conditioning and its impact on thermal comfort and energy performance - a review, Renew. Sustain. Energy Rev. 34 (2014) 401–408, https://doi.org/10.1016/j.rser.2014.03.024.

[5] M.A. Ortiz, S.R. Kurvers, P.M. Bluyssen, A review of comfort, health, and energy use: understanding daily energy use and wellbeing for the development of a new approach to study comfort, Energy Build. 152 (2017) 323–335, https://doi.org/10.1016/j.enbuild.2017.07.060.

[6] F. Fantozzi, G. Lamberti, F. Leccese, G. Salvadori, The indoor thermal environment in fencing Halls: assessment of the environmental conditions through an objective and subjective approach, in: W. Karwowski, R.S. Goonetilleke, S. Xiong, R.H. M. Goossens, A. Murata (Eds.), Advances in Physical, Social & Occupational Ergonomics, Springer International Publishing, Cham, 2020, pp. 223–229.

[7] T. Carmenate, P. Inyim, N. Pachekar, G. Chauhan, L. Bobadilla, M. Batouli, A. Mostafavi, Modeling occupant-building-appliance interaction for energy waste analysis, Procedia Eng. 145 (2016) 42–49, https://doi.org/10.1016/j.proeng.2016.04.012.

[8] J. Li, K. Panchabikesan, Z. Yu, F. Haghighat, M. el Mankibi, D. Corgier, Systematic data mining-based framework to discover potential energy waste patterns in residential buildings, Energy Build. 199 (2019) 562–578, https://doi.org/10.1016/j.enbuild.2019.07.032.

[9] P.M. Bluyssen, Towards an integrated analysis of the indoor environmental factors and its effects on occupants, Intell. Build. Int. 12 (2020) 199–207, https://doi.org/10.1080/17508975.2019.1599318.

[10] G. Lamberti, Thermal comfort in the built environment: current solutions and future expectations, in: Proceedings - 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2020, 2020, https://doi.org/10.1109/EEEIC/ICPSEurope49358.2020.9160558.

[11] M. Rocca, F. Leccese, G. Salvadori, Health and well-being in indoor work environments: features of an expert assessment campaign in an Italian university hospital, in: Proceedings - 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2020, 2020, pp. 0–5, https://doi.org/10.1109/EEEIC/ICPSEurope49358.2020.9160493.

[12] D.B. Greenberger, S. Strasser, L.L. Cummings, R.B. Dunham, The impact of personal control on performance and satisfaction, Organ. Behav. Hum. Decis. Process. 43 (1989) 29–51, https://doi.org/10.1016/0749-5978(89)90056-3.

[13] M. Frontczak, S. Schiavon, J. Goins, E. Arens, H. Zhang, P. Wargocki, Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design, Indoor Air 22 (2012) 119–131, https://doi.org/10.1111/j.1600-0668.2011.00745.x.

[14] C. Huizenga, S. Abbaszadeh, L. Zagreus, E. Arens, Air Quality and Thermal Comfort in Office Buildings: Results of a Large Indoor Environmental Quality Survey, 2006. https://www.researchgate.net/publication/228348249.

[15] G. Brager, H. Zhang, E. Arens, Evolving opportunities for providing thermal comfort, Build. Res. Inf. 43 (2015) 274–287, https://doi.org/10.1080/09613218.2015.993536.

[16] S. Karjalainen, Thermal comfort and gender: a literature review, Indoor Air 22 (2012) 96–109, https://doi.org/10.1111/j.1600-0668.2011.00747.x.

[17] Z. Wang, R. de Dear, M. Luo, B. Lin, Y. He, A. Ghahramani, Y. Zhu, Individual difference in thermal comfort: a literature review, Build. Environ. 138 (2018) 181–193, https://doi.org/10.1016/j.buildenv.2018.04.040.

[18] R.J. de Dear, T. Akimoto, E.A. Arens, G. Brager, C. Candido, K.W.D. Cheong, B. Li, N. Nishihara, S.C. Sekhar, S. Tanabe, J. Toftum, H. Zhang, Y. Zhu, Progress in thermal comfort research over the last twenty years, Indoor Air 23 (2013) 442–461, https://doi.org/10.1111/ina.12046.

[19] J. van Hoof, Forty years of Fanger's model of thermal comfort: comfort for all? Indoor Air 18 (2008) 182–201, https://doi.org/10.1111/j.1600-0668.2007.00516.x.

[20] F. Fantozzi, G. Lamberti, R. Rugani, Thermal comfort in university classrooms: analysis of simulated and real conditions, in: 2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), 2021. Bari.

[21] E. Arens, H. Zhang, C. Huizenga, Partial- and whole-body thermal sensation and comfort - Part II: non-uniform environmental conditions, J. Therm. Biol. (2006) 60–66, https://doi.org/10.1016/j.jtherbio.2005.11.027.

[22] R. Kalaimani, M. Jain, S. Keshav, C. Rosenberg, On the interaction between personal comfort systems and centralized HVAC systems in office buildings, Adv. Build. Energy Res. 14 (2020) 129–157, https://doi.org/10.1080/17512549.2018.1505654.

[23] R. Rawal, M. Schweiker, O.B. Kazanci, V. Vardhan, Q. Jin, L. Duanmu, Personal comfort systems: a review on comfort, energy, and economics, Energy Build. 214 (2020), 109858, https://doi.org/10.1016/j.enbuild.2020.109858.

[24] W. Song, Z. Zhang, Z. Chen, F. Wang, B. Yang, Thermal comfort and energy performance of personal comfort systems (PCS): a systematic review and meta-analysis, Energy Build. 256 (2022), 111747, https://doi.org/10.1016/j.enbuild.2021.111747.

[25] M. Luo, Z. Wang, H. Zhang, E. Arens, D. Filingeri, L. Jin, A. Ghahramani, W. Chen, Y. He, B. Si, High-density thermal sensitivity maps of the human body, Build. Environ. 167 (2020), https://doi.org/10.1016/j.buildenv.2019.106435.

[26] E. Arens, H. Zhang, C. Huizenga, Partial- and whole-body thermal sensation and comfort - Part I: uniform environmental conditions, J. Therm. Biol. (2006) 53–59, https://doi.org/10.1016/j.jtherbio.2005.11.028.

[27] H. Zhang, E. Arens, C. Huizenga, T. Han, Thermal sensation and comfort models for non-uniform and transient environments, part III: whole-body sensation and comfort, Build. Environ. 45 (2010) 399–410, https://doi.org/10.1016/j.buildenv.2009.06.020.

[28] A. Warthmann, D. Wölki, H. Metzmacher, C. van Treeck, Personal Climatization Systems-A Review on Existing and Upcoming Concepts, Applied Sciences (Switzerland), 2018, p. 9, https://doi.org/10.3390/app9010035.

[29] K. Tsuzuki, E. Arens, F. Bauman, D. Wyon, Individual thermal comfort control with desk-mounted and floor-mounted task/ambient conditioning (TAC) systems, in: Indoor Air, vol. 99, 1999. August 8-13, Edinburgh, 7pp.

[30] H. Zhang, E. Arens, D.E. Kim, E. Buchberger, F. Bauman, C. Huizenga, Comfort, perceived air quality, and work performance in a low-power task-ambient conditioning system, Build. Environ. 45 (2010) 29–39, https://doi.org/10.1016/j.buildenv.2009.02.016.

[31] S.B. Godithi, E. Sachdeva, V. Garg, R. Brown, C. Kohler, R. Rawal, A review of advances for thermal and visual comfort controls in personal environmental control (PEC) systems, Intell. Build. Int. 11 (2019) 75–104, https://doi.org/10.1080/17508975.2018.1543179.

[32] H. Zhang, E. Arens, Y. Zhai, A review of the corrective power of personal comfort systems in non-neutral ambient environments, Build. Environ. 91 (2015) 15–41, https://doi.org/10.1016/j.buildenv.2015.03.013.

[33] S. Shahzad, J.K. Calautit, K. Calautit, B. Hughes, A.I. Aquino, Advanced personal comfort system (APCS) for the workplace: a review and case study, Energy Build. 173 (2018) 689–709, https://doi.org/10.1016/j.enbuild.2018.02.008.

[34] H. Zhang, E. Arens, M. Taub, D. Dickerhoff, F. Bauman, M. Fountain, W. Pasut, D. Fannon, Y. Zhai, M. Pigman, Using footwarmers in offices for thermal comfort and energy savings, Energy Build. 104 (2015) 233–243, https://doi.org/10.1016/j.enbuild.2015.06.086.

[35] M. Luo, E. Arens, H. Zhang, A. Ghahramani, Z. Wang, Thermal comfort evaluated for combinations of energy-efficient personal heating and cooling devices, Build. Environ. 143 (2018) 206–216, https://doi.org/10.1016/j.buildenv.2018.07.008.

[36] T. Hoyt, E. Arens, H. Zhang, Extending air temperature setpoints: simulated energy savings and design considerations for new and retrofit buildings, Build. Environ. 88 (2015) 89–96, https://doi.org/10.1016/j.buildenv.2014.09.010.

[37] T. Parkinson, R. de Dear, C. Candido, Thermal pleasure in built environments: alliesthesia in different thermoregulatory zones, Build. Res. Inf. 44 (2016) 20–33, https://doi.org/10.1080/09613218.2015.1059653.
[38] T. Parkinson, R. de Dear, Thermal pleasure in built environments: physiology of alliesthesia, Build. Res. Inf. 43 (2015) 288–301, https://doi.org/10.1080/09613218.2015.989662.
[39] P. Jiang, Y. van Fan, J.J. Klemeš, Impacts of COVID-19 on energy demand and consumption: challenges, lessons and emerging opportunities, Appl. Energy 285 (2021), https://doi.org/10.1016/j.apenergy.2021.116441.
[40] R. Rugani, M. Picco, G. Salvadori, M. Marengo, F. Fantozzi, Can PCS help us save energy? Initial assessment using dynamic energy and CFD analyses, in: 2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), 2021. Bari.
[41] M. Hannon, D. Brown, Energy Discounts Are a Sticking Plaster - Here's a Long-Term Solution to Soaring Household Bills, The Conversation, 2022. https://theconversation.com/energy-discounts-are-a-sticking-plaster-heres-a-long-term-solution-to-soaring-household-bills-176402. (Accessed 2 January 2023).
[42] ASHRAE, ANSI/ASHRAE Standard 55: "Thermal Environmental Conditions for Human Occupancy, 2020.
[43] ISO 7730:2005, Ergonomics of, The Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, 2005.
[44] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE global thermal comfort Database II, Build. Environ. 153 (2019) 205–217, https://doi.org/10.1016/j.buildenv.2019.01.055.
[45] L. Schellen, M.G.L.C. Loomans, M.H. de Wit, B.W. Olesen, W.D. van Marken Lichtenbelt, The influence of local effects on thermal sensation under non-uniform environmental conditions — gender differences in thermophysiology, thermal comfort and productivity during convective and radiant cooling, Physiol. Behav. 107 (2012) 252–261, https://doi.org/10.1016/j.physbeh.2012.07.008.
[46] T.J. Doherty, E. Arens, Evaluation of the physiological bases of thermal comfort models, Build. Eng. 94 (1988) 1371–1385. https://www.scopus.com/inward/record.uri?eid=2-s2.0-0009838807&partnerID=40&md5=f3a920a7e73a5cc9893c6e3ac674597d.
[47] H. Du, Z. Lian, D. Lai, L. Duanmu, Y. Zhai, B. Cao, Y. Zhang, X. Zhou, Z. Wang, X. Zhang, Z. Hou, Comparison of thermal comfort between radiant and convective systems using field test data from the Chinese Thermal Comfort Database, Build. Environ. 209 (2022), 108685, https://doi.org/10.1016/j.buildenv.2021.108685.
[48] B. Yang, W. Su, Z. Ai, F. Wang, Effect of a novel personal comfort device on occupants' perceptual responses in three warm indoor environments, Indoor Built Environ. 0 (2022), https://doi.org/10.1177/1420326X221145860, 1420326X221145860.
[49] W. Su, B. Yang, B. Zhou, F. Wang, A. Li, A novel convection and radiation combined terminal device: its impact on occupant thermal comfort and cognitive performance in winter indoor environments, Energy Build. 246 (2021), 111123, https://doi.org/10.1016/j.enbuild.2021.111123.
[50] Y. He, T. Parkinson, E. Arens, H. Zhang, N. Li, J. Peng, J. Elson, C. Maranville, Creating alliesthesia in cool environments using personal comfort systems, Build. Environ. 209 (2022), 108642, https://doi.org/10.1016/j.buildenv.2021.108642.
[51] W. Luo, R. Kramer, Y. de Kort, P. Rense, W. van Marken Lichtenbelt, The effects of a novel personal comfort system on thermal comfort, physiology and perceived indoor environmental quality, and its health implications - stimulating human thermoregulation without compromising thermal comfort, Indoor Air 32 (2022), e12951, https://doi.org/10.1111/ina.12951.
[52] R. Rugani, M. Bernagozzi, M. Picco, F. Fantozzi, A novel personal comfort system: a radiant desk with a Loop heat pipe, in: BSA - Building Simulation Applications, Bolzano, 2022.
[53] YuF. Maydanik, Loop heat pipes, Appl. Therm. Eng. 25 (2005) 635–657, https://doi.org/10.1016/j.applthermaleng.2004.07.010.
[54] ASHRAE, Handbook of Fundamentals, 2021.
[55] Y. Tang, H. Yu, K. Zhang, K. Niu, H. Mao, M. Luo, Thermal comfort performance and energy-efficiency evaluation of six personal heating/cooling devices, Build. Environ. (2022) 217, https://doi.org/10.1016/j.buildenv.2022.109069.
[56] P.O. Fanger, Thermal Comfort: Analysis and Applications in Environmental Engineering, Danish Technical Press, 1970. https://books.google.it/books?id=S0FSAAAAMAAJ.
[57] ISO, ISO 11855-1:2021, "Building Environment Design — Embedded Radiant Heating and Cooling Systems. Part 1: Definitions, Symbols, and Comfort Criteria, 2021.
[58] S. Liu, Z. Wang, S. Schiavon, Y. He, M. Luo, H. Zhang, E. Arens, Predicted percentage dissatisfied with vertical temperature gradient, Energy Build. 220 (2020), https://doi.org/10.1016/j.enbuild.2020.110085.
[59] Y. He, N. Li, L. Zhou, K. Wang, W. Zhang, Thermal comfort and energy consumption in cold environment with retrofitted Huotong (warm-barrel), Build. Environ. 112 (2017) 285–295, https://doi.org/10.1016/j.buildenv.2016.11.044.
[60] H. Wang, W. Li, J. Wang, M. Xu, B. Ge, Experimental Study on Local Floor Heating Mats to Improve Thermal Comfort of Workers in Cold Environments, Building and Environment, 2021, p. 205, https://doi.org/10.1016/j.buildenv.2021.108227.
[61] H. Yang, B. Cao, Y. Zhu, Study on the effects of chair heating in cold indoor environments from the perspective of local thermal sensation, Energy Build. 180 (2018) 16–28, https://doi.org/10.1016/j.enbuild.2018.09.003.
[62] H. Oi, K. Yanagi, K. Tabata, Y. Tochihara, Effects of heated seat and foot heater on thermal comfort and heater energy consumption in vehicle, Ergonomics 54 (2011) 690–699, https://doi.org/10.1080/00140139.2011.595513.
[63] G. Havenith, K. Griggs, Y. Qiu, L. Dorman, V. Kulasekaran, S. Hodder, Higher comfort temperature preferences for anthropometrically matched Chinese and Japanese versus white-western-middle-European individuals using a personal comfort/cooling system, Build. Environ. 183 (2020), 107162, https://doi.org/10.1016/j.buildenv.2020.107162.