

Review

Effective Heat Transfer Mechanisms of Personal Comfort Systems for Thermal Comfort and Energy Savings: A Review

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Abstract

Personal comfort systems (PCSs), which provide targeted heating or cooling to specific body parts, have emerged as a promising solution to enhance occupant comfort while reducing energy use in buildings. Among the many factors influencing PCS performance, heat transfer mechanisms (HTMs) play a pivotal role. However, a critical gap remains in the literature regarding the identification of optimal HTMs for achieving both thermal comfort and energy efficiency in PCSs. To address this gap, our study investigates the impact of conduction, convection, and radiation in PCSs on thermal comfort enhancement and energy performance under both heating and cooling modes. A meta-analysis was conducted, extracting data from 64 previous studies to evaluate the effects of HTMs of PCSs on thermal sensation vote (TSV), overall comfort (OC) and corrective energy power (CEP). Results indicate that PCSs typically improve users' thermal sensation and comfort by about one scale unit in both heating and cooling modes. Radiative HTM is the most effective individual method, while combined conductive and convective HTMs perform best overall. Most PCSs operate efficiently, consuming less than 200 W/°C, with conduction in heating and convection in cooling being recommended for optimal comfort and energy efficiency. These findings suggest that selecting optimal HTMs for PCSs is crucial for achieving maximum comfort performance and energy savings. Data on combined HTMs of PCSs remain limited, underscoring the need for further research in this area. Future research should prioritize optimizing HTMs, especially radiative and combined methods, to maximize comfort and energy savings in PCS design.

Keywords: personal comfort systems; meta-analysis; thermal sensation; overall comfort; heat transfer mechanism; energy efficiency



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1. Introduction

1.1. Overview

High energy consumption in buildings remains a critical global challenge and constitutes approximately about 30% of global energy consumption [1]. Heating, ventilation and air conditioning (HVAC) systems are consuming about half of total building energy usage [2]. HVAC systems typically achieve thermal comfort satisfaction for approximately 80% of occupants [3]. Integration of personal comfort systems (PCSs) has shown significant improvements in occupant satisfaction and energy savings [4,5]. Several factors affect PCS performance, and the heat transfer mechanism (HTM) plays a critical role in shaping the effectiveness of PCSs by influencing thermal perception and energy efficiency [4].

The selection of the appropriate heat transfer mechanism in PCSs, such as convective, conductive, or radiative, determines the extent to which these systems can provide targeted, individualized comfort while maximizing energy savings [6,7]. Recent research highlights that local heating or cooling using the optimal HTM can address zones of higher thermal sensitivity on the human body, thereby significantly enhancing overall comfort [8,9]. Different HTMs can also be employed simultaneously by various PCS devices to optimize both comfort and energy efficiency [10–14]. However, the specific role of HTMs in PCS design remains insufficiently explored. Identifying the optimal HTMs is essential, as this knowledge can guide the development of more effective PCSs capable of enhancing occupant comfort while achieving energy-saving targets.

1.2. PCS Performance and Heat Transfer Mechanisms (HTMs)

Various types of PCS devices have been developed and implemented to regulate thermally sensitive areas of the human body, allowing thermal comfort to be maintained across a wider range of ambient conditions [15,16]. The primary tasks of PCSs include improving occupant satisfaction through individualized thermal control [15]. Participants have experienced around 96% thermal acceptability and 99% satisfaction when using PCSs [3,5]. PCSs provide heating or cooling to the person directly, rather than the entire space or building, which is much more energy-intensive [9]. This will increase energy savings by using less energy compared to traditional HVAC systems and enabling broader temperature setpoints while also promoting building resilience and sustainability by reducing overall energy demands [3,5,15].

To measure this comfort performance of PCSs, thermal sensation vote (*TSV*) and overall comfort (*OC*) are essential and commonly used. These metrics assess the thermal conditions and their impact on human comfort [17–19]. These subjective measures provide valuable insights into occupants' perceptions and satisfaction with their thermal surroundings. A 7-point scale is commonly used for the *TSV* scale, which ranges from cold to hot [20]. This scale allows individuals to report their perceived thermal state, which can be influenced by various factors, including environmental and personal factors [21,22]. *OC* measures an individual's general satisfaction with their environment, taking into account multiple factors beyond just thermal conditions [21]. This metric often employs a scale that ranges from very uncomfortable to very comfortable, providing a holistic view of occupant well-being.

Recently, corrective energy power (*CEP*) has been introduced to measure the energy performance of PCS devices [23,24]. *CEP* is linked with corrective power (*CP*), which is a metric used to quantify the effectiveness of PCSs in thermal comfort research. It represents the temperature difference between two ambient conditions that produce equal thermal sensations—one without PCSs and one with PCSs in use [10,25]. *CP* essentially measures how much a PCS can regulate the ambient temperature towards thermal neutrality. *CP* can be used as an indicator for identifying thresholds of ambient temperature correction by PCSs. *CPE* assesses the energy efficiency of PCS devices in relation to their comfort-improving capabilities. *CPE* links a device's *CP* to its energy use, making it easier to compare different PCS technologies based on their efficiency in providing thermal comfort [25].

Research on thermal comfort is inherently complex, as multiple interacting factors influence human perception. Luo et al. [4] stated that the effectiveness of PCSs is mainly affected by three factors: environmental factors, personal factors and system factors. There are several system factors, such as targeted body segments, cooling/heating area, power output and HTMs. Song et al. [9] categorized HTMs in PCSs into conductive (*Cd*), convective (*Cv*) and radiative (*Rd*) mechanisms. Conduction transfers heat through direct

molecular contact within solids. Convection moves heat via fluid motion, where warmer fluid rises and cooler fluid sinks. Radiation transfers heat through electromagnetic waves without needing a medium [9,26].

Previous experimental studies on PCS devices have primarily focused on improving occupant thermal comfort and assessing energy-saving potential in buildings. However, the influence of heat transfer modes on perceptual responses has received limited attention [27]. Consequently, theoretical analyses that explain the role of heat transfer mechanisms remain insufficient, highlighting the need for further experimental research to support the optimization of localized comfort strategies.

1.3. Research Gap and Objectives

Understanding and applying optimal heat transfer mechanisms in PCSs is crucial, as they govern the efficiency of localized heating and cooling delivered to the human body [4]. Optimized HTMs in PCSs improve thermal comfort while reducing reliance on energy-intensive whole-building conditioning. Table 1 shows the current reviews and their studied parameters on PCSs. Previous research, such as Song et al. [9] and Xu et al. [28], has applied effect size methods to assess the performance of various PCS types; however, none of them have explicitly examined the impact of different HTMs on both the comfort and energy performance of PCSs. Song et al. [9] reviewed the performance of a range of PCS types but did not explicitly address the role of HTMs on comfort and energy; moreover, their analysis was limited to 34 articles. Du and Ghahramani [29] evaluated the changes in *TSV* produced by different HTMs within PCSs; however, their analysis did not employ effect size methods and was limited solely to *TSV* outcomes.

Previous literature reviews evaluated PCS performance and nature studies with different objectives but did not explicitly examine HTMs' impact on their performance using effect size methods incorporating the widely accepted performance metrics for PCSs, such as *TSV*, *OC*, *CP* and *CEP*. Because PCSs are human sample-based experiments, Hedges' effect size is crucial in meta-analyses because it standardizes group differences by accounting for both sample variance and measurement scales, allowing the results from diverse studies to be meaningfully pooled and compared. Its bias correction for small samples and reliance on statistical precision make it much more reliable and interpretable than using mean values alone, which can be misleading due to the differences in measurement units and variance [30,31].

To the best of our knowledge, no study has systematically explored and reviewed how HTMs impact the comfort performance through effect size analyses of *TSV* and *OC*, identified setpoint thresholds using *CP*, and evaluated energy efficiency using *CEP* of PCSs, indicating a critical gap in the literature [27]. Figure 1 illustrates the identified research gap for this study. PCSs are utilized for both heating and cooling, with conduction, convection, and radiation as the primary HTMs. Comfort performance is typically evaluated using *TSV* and *OC*. Ambient temperature correction capacity is measured using corrective power, while corrective energy power serves as the key parameter for assessing PCS energy efficiency. As the figure explains, there was no study that explored how HTMs affect *TSV* and *OC* as the comfort parameters and *CEP* as the energy efficiency parameters of PCSs.

This study aims to address this gap by conducting a meta-analysis of 64 relevant articles to investigate the impact of different heat transfer mechanisms on the thermal comfort and energy performance of personal comfort systems in both heating and cooling modes. To evaluate PCS performance, this study employs thermal sensation vote (*TSV*) and overall comfort (*OC*) as indicators of comfort, corrective power (*CP*) as an indicator for thermal ambient improvement, and corrective energy power (*CEP*) as a measure of energy efficiency. The primary objective is to provide a comprehensive understanding of

how HTMs influence PCS effectiveness and finding the most effective and energy-efficient HTMs, thereby informing future design and application strategies.

Table 1. Previous literature reviews on personal comfort systems.

Study	Number of Included Studies	Main Focus	Heat Transfer Mechanisms	Effect Size	TSV	OC	CP	CEP
Song et al. [9]	34	Effects of PCSs on occupants' perceptual responses.	Discussed superficially. Did not analyze HTMs category-wise	✓	✓	✓	✗	✓
Xu et al. [28]	25	Effects of PCSs on sleep.	Discussed qualitatively	✓	✗	✓	✗	✗
Du and Ghahramani [29]	83	PCS performance and experiment design.	Discussed with TSV differences	✗	✓	✗	✗	✗
Rawal et al. [8]	184	Effectiveness, energy savings, and cost of PCSs.	Discussed qualitatively	✗	✓	✓	✓	✗
Cao and Xie [32]	52	Wearable device types and factors affecting user satisfaction.	Discussed qualitatively	✗	✓	✓	✗	✗
Warthmann et al. [33]	59	Summarized personal climatization systems' research.	Discussed qualitatively	✗	✓	✓	✗	✗
Zhang et al. [25]	41	Quantifying ability of PCSs in providing comfort in various ambient temperatures.	Discussed qualitatively	✗	✓	✓	✓	✗
Luo et al. [4]	32	Effects of PCSs on local body segments in office settings.	Discussed qualitatively	✗	✓	✗	✗	✗
Exss et al. [16]	120	Classifying PCSs based on post-phenomenological mediation categories.	Discussed qualitatively	✗	✗	✗	✗	✗
Shahzad et al. [34]	16	PCSs' ability to reduce energy, maintain comfort, and improve air quality.	Not discussed	✗	✓	✓	✗	✗

✓: Discussed in the study. ✗: Not discussed in the study.

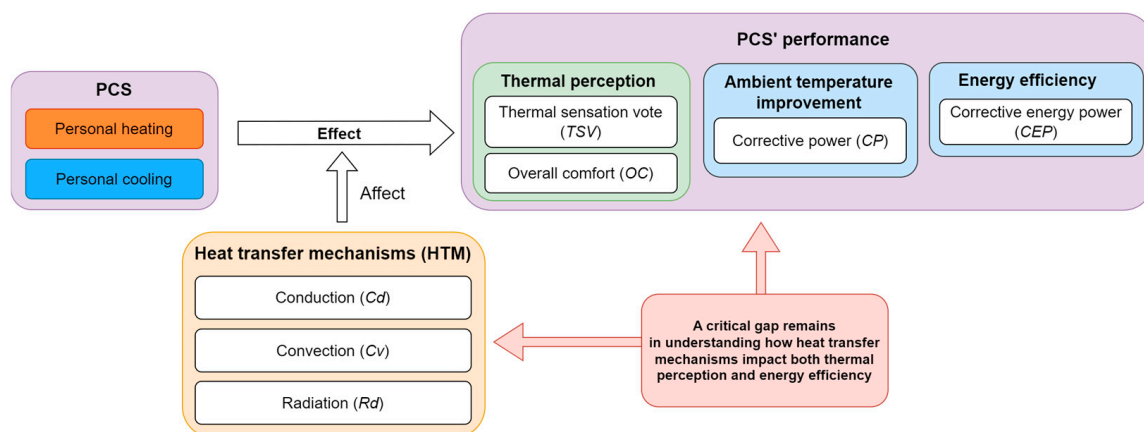


Figure 1. Identified research gap in PCS studies.

2. Methodology

2.1. Literature Search and Selection Criteria

An extensive literature review was conducted, yielding many potential publications from the Scopus database and published review papers. A search was conducted in the Scopus database to identify studies related to PCSs and occupant thermal responses in heating and cooling modes. The formulated search string was “personal AND comfort AND (system OR device) AND (sensation OR subject)”. In addition to that, research papers that were included in other PCS review papers [8,9,16,32–34] were collected as well.

After the collection, all the papers were processed through the screening process to select suitable articles for this meta-analysis. The publication selection process is illustrated in Figure 2. Initially, studies that were not in English, as well as those consisting only of abstracts or unpublished theses, were excluded. Subsequently, publications were selected based on the following criteria aligned with this study’s objectives:

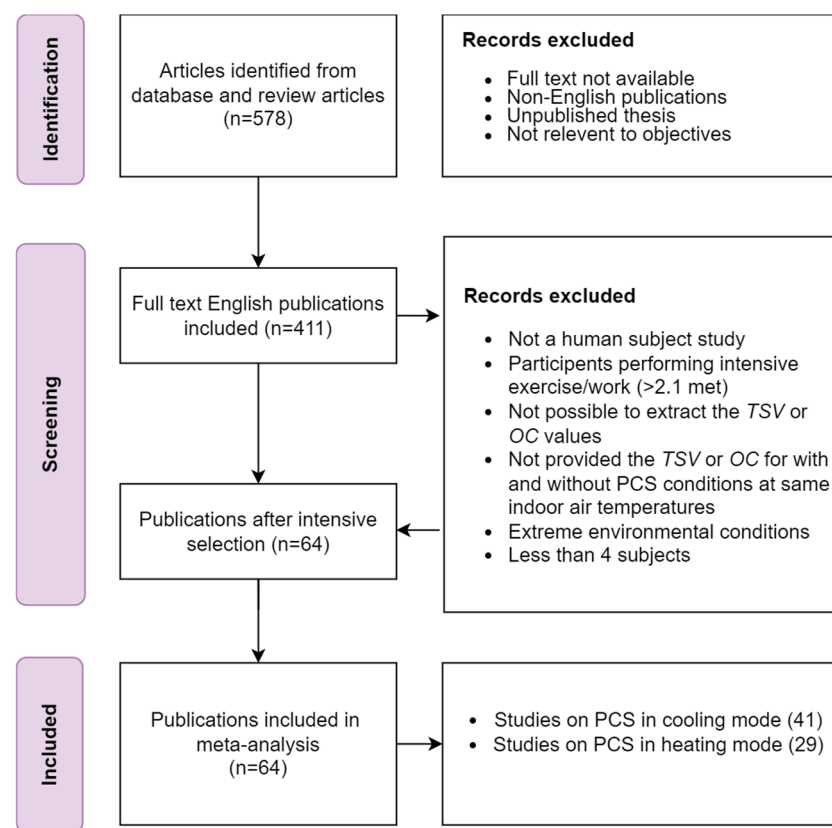


Figure 2. Flow chart of publication selection process.

1. Human trials were conducted in laboratory settings under steady-state thermal conditions or lower thermal conditions on varying field studies.
2. PCSs had to be implemented in indoor environments where participants were sitting, standing, or engaging in low-intensity activities (i.e., metabolic rate < 2.1 met).
3. PCSs were required to be used in environments with high or low air temperatures, primarily aimed at achieving thermal comfort.
4. Studies were required to be randomized controlled trials, where participants were assigned to either cooling/heating interventions or control trials.
5. Studies had to report participants’ overall perceptual responses in thermal sensation vote, overall comfort, or thermal acceptability using widely accepted scales based on the body thermal state.
6. Studies with a number of subjects higher than four people.

7. Studies had to report thermal sensation, overall comfort, or thermal acceptability values in graphs on an accurate scale or in numbers with relevant and the same indoor air temperatures for conditions with and without PCSs.

For this study, 476 TSV values and 431 OC values were extracted for both conditions with and without PCSs in the same indoor air temperatures from 64 original research works. In total, 287 power values of the devices were recorded from papers in which data was available.

2.2. Data Collection

Data was collected from original PCS studies following meta-analysis methodologies [35]. Heating and cooling PCS devices are classified according to their intended purpose and their impact within the relevant environment, following the approach of Song et al. [9]. The mean whole-body TSV and OC values in the same indoor air temperature were extracted for conditions with PCSs and without PCSs. In cases where exact TSV and OC values were not provided in the text, TSV and OC graphs were utilized for data extraction and LabPlot 2.12.0 software version [36] was employed to record data points. Table 2 shows the scales of TSV and OC used for this study.

Table 2. Scale of thermal sensation vote and overall comfort.

Value	Thermal Sensation Vote (TSV)	Overall Comfort (OC)
3	Hot	Very comfortable
2	Warm	Comfortable
1	Slightly warm	Slightly comfortable
0	Neutral	Neutral
−1	Slightly cool	Slightly uncomfortable
−2	Cool	Uncomfortable
−3	Cold	Very uncomfortable

Measured TSV values were assessed based on the ASHRAE 7-point scale in all studies. Some OC scales did not follow this 7-point scale. It was normalized to a 7-point scale, where −3 represents very uncomfortable, 3 represents very comfortable, and 0 indicates neutral. This normalization was completed by linking the semantic meaning of comfort scales to the 7-point scale. Even various comfort measurement scales showed no significant differences in sensitivity when assessing physical factors [37], with the choice of the scale significantly affecting reliability and respondent perception [38]. This is a relationship closely linked to the semantic meanings of the evaluated attributes, which influence how participants perceive and report thermal comfort [37,39]. These kinds of normalization approaches were used in previous meta-analyses [40,41]. Some data points were not included, as no data was available to identify whether the heating or cooling mode of PCSs was activated during the survey. For the studies that did not explicitly provide OC values, overall thermal acceptability values were assumed to represent overall comfort values, as these have been found to be highly correlated [42]. Categorical and continuous scales of OC and TSV were considered equivalent for calculation purposes. In some studies, certain data points were excluded due to high metabolic activity levels that resulted in abnormal TSV values.

At the same time, power (W) values of the PCSs at the relevant indoor air temperatures were collected. Power values from high-consumption devices (e.g., 5090 W) were excluded only from the CEP analysis to prevent skewing the results [43]. When studies provided only a range of device power consumption along with the minimum and maximum adjustable

temperatures [44] or speed settings [45], the corresponding power values were estimated based on temperature variations, assuming a linear operational function.

2.3. Classification of Heat Transfer Mechanisms (HTMs)

Devices that come into direct contact with the subject's skin for heating or cooling purposes were classified as conductive (*Cd*) devices, those that stimulate the surrounding air to provide thermal comfort are categorized as convective (*Cv*) devices, and devices that do not make direct contact with the body, do not influence the surrounding air, and provide heating solely through radiation are considered radiative (*Rd*) devices [9]. When the PCS studies employed several HTMs simultaneously, the HRM was categorized separately by considering it as a distinct combined HTM, such as conduction with convection (*Cd & Cv*), conduction with radiation (*Cd & Rd*), convection with radiation (*Cv & Rd*), and conduction and convection with radiation (*Cd, Cv & Rd*).

When categorizing PCS devices into HTM groups, some devices are primarily targeted at specific mechanisms but could also involve secondary effects. For example, the radiant cooling desk in He et al. [46] was classified under radiation and convection, although incidental hand contact may introduce a minor conduction effect. In this study, classification was based on the primary HTM of each device, acknowledging that secondary influences may exist but are not the main focus of the design.

2.4. Thermal Comfort and Energy Performance

To evaluate thermal comfort performance, this study used the standardized mean difference effect sizes and 95% confidence intervals of *TSV* and *OC*. This allowed us to evaluate the effects of the use of PCSs on improving thermal comfort for both *TSV* and *OC*. The bias-corrected Hedges effect size was adopted to overcome drawbacks associated with the small sample size [47]. Mean and standard deviation values of *TSV* and *OC* for conditions with and without PCSs for each HTM and the mean subject sample size of each HTM were employed for calculating effect sizes using Equation (1) [31,48].

$$\text{Hedges' } g = \frac{M_{\text{with PCS}} - M_{\text{without PCS}}}{SD_{\text{Pooled}}} \times J \quad (1)$$

where $M_{\text{with PCS}}$ is the mean of *TSV* or *OC* with PCS and $M_{\text{without PCS}}$ is the mean of *TSV* or *OC* without a PCS for each HTM category. J is Hedges' correction factor.

$$SD_{\text{Pooled}} = \sqrt{\frac{(N_{\text{with PCS}} - 1)SD_{\text{with PCS}}^2 + (N_{\text{without PCS}} - 1)SD_{\text{without PCS}}^2}{N_{\text{with PCS}} + N_{\text{without PCS}} - 2}} \quad (2)$$

where $N_{\text{with PCS}}$ is the number of cases of *TSV* or *OC* with PCS and $N_{\text{without PCS}}$ is the number of cases of *TSV* or *OC* without a PCS for each HTM category.

$SD_{\text{with PCS}}$ and $SD_{\text{without PCS}}$ are the standard deviations of *TSV* or *OC* for conditions with and without a PCS for each HTM category.

$$J = 1 - \frac{3}{4(N_{\text{with PCS}} + N_{\text{without PCS}}) - 9} \quad (3)$$

Statistical heterogeneity was assessed to determine the proportion of variability in effect estimates. When moderate heterogeneity (I^2 between 50% and 75%) or high heterogeneity ($I^2 > 75\%$) was observed, a random-effect model was applied to compute the pooled intervention effect. In cases of low heterogeneity, a fixed-effect model was used instead [49]. The weighted mean effect size was calculated by assigning weights to each study based on its precision [50].

The equations used for weighting were as follows:

$$\text{Fixed effect model : } W_c = \frac{1}{V_c} \quad (4)$$

$$\text{Random effects model : } W_c = \frac{1}{V_c + \tau^2} \quad (5)$$

where W_c is the weight of the category, V_c is the variance of the category, and τ^2 represents between-study variability.

Effect sizes were categorized as follows: $0 \sim \pm 0.19$ (negligible), $\pm(0.2 \sim 0.49)$ (small), $\pm(0.5 \sim 0.79)$ (moderate), and ± 0.8 or above (large) [51]. To further validate the effect size findings, Pearson's correlation analysis was conducted to examine the relationship between *TSV* and *OC* across different heat transfer mechanisms.

To measure the energy efficiency of PCSs in achieving thermal comfort for occupants, this study employed corrective energy power (*CEP*, $W/^\circ\text{C}$), which is a widely used parameter in PCS studies [24,52]. *CEP* is defined as the quantification of power needed for adjusting an individual's thermal perception towards comfortable perception by particular heating or cooling PCSs [24,52]. Although *CP* can be determined by correcting ambient temperature, this study calculated it using *TSV* differences [25,53], as the primary focus was on subjective perception and *TSV* reflects the subject's perception about the dynamic environment with PCSs. *CP* and *CEP* exhibit negative values in cooling mode and positive values in heating mode, reflecting decreases or increases in perceived ambient temperature attributable to PCS interventions, respectively. To avoid potential confusion arising from these opposing directional values when evaluating PCS performance, absolute values of *CP* and *CEP* were employed throughout this analysis.

Absolute *CP* and *CEP* were calculated using the following equations:

$$\text{Absolute } CP = \text{Absolute } \Delta TSV / G \quad (6)$$

$$\text{Absolute } CEP = P / |CP| \quad (7)$$

where P is the power value of the PCS device and ΔTSV is $TSV_{\text{With PCS}} - TSV_{\text{Without PCS}}$.

G is Griffiths' constant, and it is assumed to be 0.33, consistent with Franger [54], as over 80% of the referenced studies were conducted in climate chambers or semi-controlled environments. Reported values of $1/G$ range from 2 to 6 $^\circ\text{C}$ per Likert scale unit [53], influenced by occupancy type and PCS coverage. Thermal sensitivity is typically higher in air-conditioned spaces ($a = 0.44 \sim 0.47$ sensation units/ $^\circ\text{C}$) than in naturally ventilated buildings ($a = 0.21 \sim 0.22$) [55,56], with field studies in China showing variations around 0.3 (0.26–0.32) [57]. Given that most included studies are from China, a mid-range value of 3.0 $^\circ\text{C}$ per scale unit ($a = 0.33$) was selected, aligning with ASHRAE and ISO comfort zone specifications [53,58].

For the *CEP* comparison, the mean absolute *CEP* values with a 95% confidence interval (mean ± 2 S.E.) of different HTMs for heating and cooling modes were analyzed.

3. Results and Discussion

3.1. Description of Data Analyzed

Data on various types of PCSs were extracted from the selected 64 studies. Table A1. shows the PCS devices included, their HTMs, the number of subjects participated in experiment and the power values of the PCS devices under cooling or heating mode. Studies have employed various kinds of conductive, convective, and radiative PCSs to provide comfort in both heating and cooling settings. Some studies have employed combined HTMs. There

were 41 and 29 studies covering cooling and heating modes, respectively. Overall, 33% of the studies employed 20 or 16 subjects for their studies, and 50% of the studies employed 16 or less subjects. More than 70% of the experiments in the included studies were conducted in climate chambers. There was a 0.6 to 630 W range of power values reported for the devices. Generally, heating PCSs show higher power values compared to cooling PCSs.

PCSs employ three primary heat transfer mechanisms—conduction, convection, and radiation—through diverse device architectures tailored to specific thermal delivery requirements. Conductive systems predominantly utilize direct contact heating/cooling through electrically heated elements embedded in chairs, mats, and wearable devices. Notable examples include heated chairs with silicone rubber heaters positioned between leather and polyurethane layers [59], carbon fiber heating elements integrated into seat cushions and backrests [60], and thermoelectric cooling chairs employing semiconductor chilling plates (45 W each) coupled with flat heat pipes for a uniform temperature distribution [61]. Wearable conductive devices range from heated insoles using carbon crystal heating films [10] to sophisticated thermoelectric heat pump modules like the Embr Wave system, which delivers precise temperature profiles (25–42 °C) across a 6.25 cm² contact area using the Peltier effect [62]. Convective systems primarily employ fan-based architectures, from simple desk fans delivering localized airflow (0.05–2.5 m/s) to complex task-ambient conditioning systems integrating under-floor air distribution with personalized ventilation [63]. Advanced convective designs include ventilation clothing with integrated 9.8 cm diameter fans powered by rechargeable batteries [64] and ceiling-mounted oscillating fans with customized mounting structures for optimal air distribution [65]. Radiant systems utilize infrared heating through reflector lamps enclosed in insulated chambers [66], water-cooled aluminum panels with capillary tube networks for radiant cooling [11], and portable thermoelectric cooling partitions featuring 12 Peltier elements arranged in thermal zones corresponding to seated occupant body segments [67].

The systematic analysis of targeted body parts in PCSs reveals distinct physiological targeting strategies that leverage human thermoregulatory characteristics and thermal sensitivity variations. Head, face, and neck regions represent the most frequently targeted areas (about ~57% of studies), primarily through convective cooling via desk fans, ceiling fans, and personalized ventilation systems, reflecting the high density of thermoreceptors and the significant contribution of cranial heat loss to the overall thermal sensation. Extremities constitute critical thermal comfort intervention points, with hands, wrists, and arms targeted in ~30% of studies through heated desk surfaces, wristbands, and hand-warming devices; legs and feet received attention in ~39% of studies via heated floor mats, foot warmers, and leg-warming systems, capitalizing on the pronounced vasoconstriction responses in peripheral circulation that disproportionately affect whole-body thermal perception. Torso targeting shows sophisticated regional differentiation, with front torso applications (about 40% of studies) focusing on convective cooling through fans and cooling garments, while back torso interventions (about 44% of studies) predominantly employ conductive heating through chair-integrated systems and heated clothing. The buttocks' region, targeted in approximately 29% of studies exclusively through heated seating systems, represents a high-contact surface area with significant potential for conductive heat transfer. Multi-zone approaches demonstrate increasing sophistication, exemplified by hybrid systems combining extremity heating (foot warmers, wrist pads) with head/torso cooling (desk fans, cooling chairs), reflecting an understanding that effective PCSs must address the complex thermal gradients and regional preferences that characterize human thermal comfort in indoor environments [10,68].

Among the data collected, the HTMs were not equally distributed; for some HTMs, there was no data available in the literature, as shown in Table A2. *Cd* and *Cv* HTMs have

the highest number of data, while *Rd* has a lower amount of data. All other combined HTMs have very few data. Previous studies have not studied employing several HTMs simultaneously in PCSs broadly, and many studies have not provided the power values of the studied PCSs. These variances in available data indicate the importance of focusing studies on the combined HTMs of PCSs.

3.2. Overall Impact of PCSs on Perceptual Responses

Perceptual responses are important for measuring human thermal comfort. *TSV* provides a measurement on how people feel at certain environment [69], while *OC* offers a measure of comfort accumulating with the combined effects of other environmental factors [70,71]. Higher *TSV* values indicate a hot-side thermal sensation, while lower values indicate a cold-side sensation. Similarly, higher *OC* values correspond to greater comfort, whereas lower values reflect increased discomfort. Together, these indices complement objective environmental measurements by linking physical conditions with subjective human experience, thereby providing a comprehensive understanding of thermal comfort in diverse settings.

Figure 3 shows the distribution of *TSV* in heating and cooling modes with and without PCS conditions. In both heating and cooling scenarios, the PCS significantly shifts the mean thermal sensation vote closer to neutral (0), reducing feelings of being cold or hot. The mean *TSV* improved by about 1 scale unit with PCSs for both heating and cooling modes toward neutral. The standard deviation, representing the spread of sensations, remained relatively consistent, indicating that the PCS effectively adjusts the average perceived temperature without drastically altering individual variability in thermal comfort.

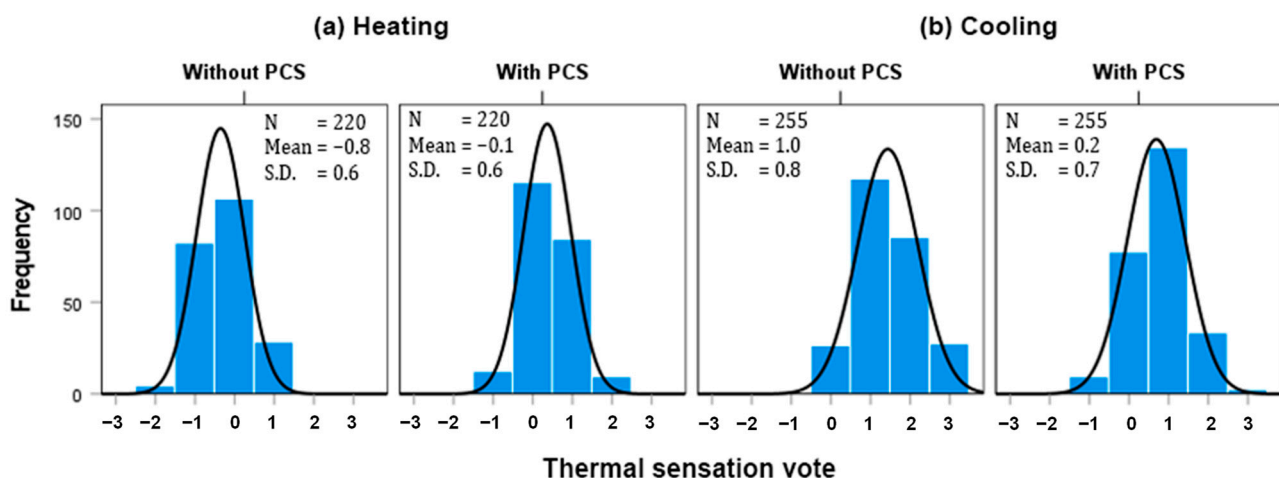


Figure 3. Distribution of thermal sensation vote in (a) heating and (b) cooling modes.

Figure 4 shows the distributions of *OC* in heating and cooling modes for conditions with and without PCSs. Both in heating and cooling modes, the mean *OC* value indicates slight discomfort without PCSs, which shifts towards comfort with PCSs by about 1 scale unit. The standard deviations also show a slight decrease with PCSs in both cases, indicating a slightly more concentrated and agreeable comfort improvement when PCSs are in use in both heating and cooling modes.

The results confirm that PCSs effectively shift thermal sensations and overall comfort closer to neutral by 1 scale unit in both heating and cooling modes, improving the mean thermal sensation and reducing discomfort variability. This aligns with multiple studies, showing that PCSs can correct perceived temperatures by several degrees, enhancing occupant comfort without major changes in individual variability [8,9]. Therefore, PCSs

are effective in achieving comfort and energy savings by adjusting HVAC setpoints in both heating and cooling modes [72].

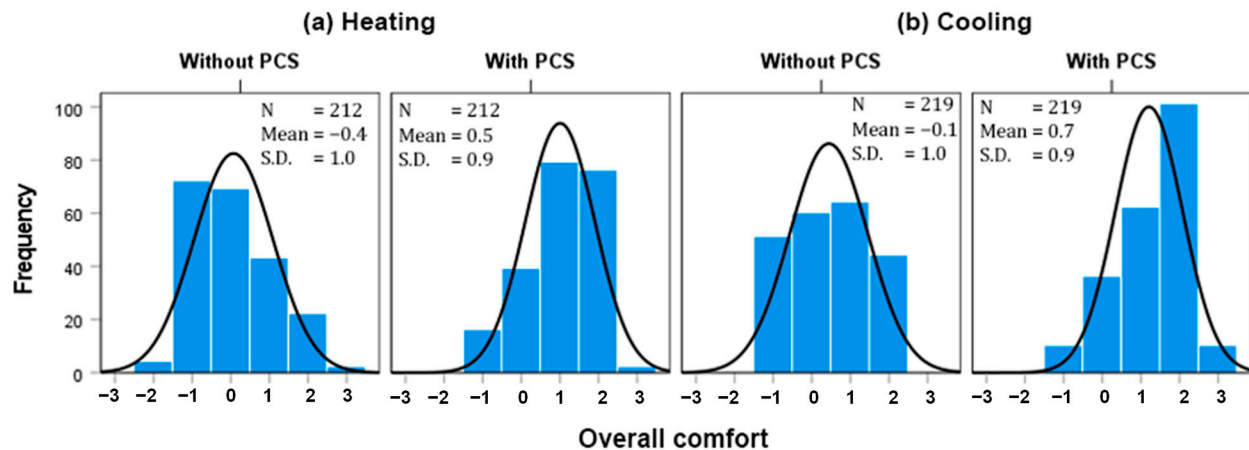


Figure 4. Distribution of overall comfort in (a) heating and (b) cooling modes.

3.3. HTMs' Impact on Thermal Comfort

The thermal comfort performance of PCS depends on various factors, and HTMs are one of them [4]. Choosing an optimum HTM in PCSs is crucial because it maximizes localized thermal comfort [27]. This study analyzed the effect size of different HTMs of PCSs on TSV and OC to evaluate the thermal comfort performance. To determine whether a fixed-effect or random-effect model was more appropriate for the analysis, tests of heterogeneity and homogeneity were conducted for both TSV and OC. The heterogeneity test I^2 value was 71% and 84% for TSV, and it was 0% and 22% for OC for the heating and cooling modes, respectively. The p value of the homogeneity test was <0.001 for TSV and 0.74 for the heating mode and 0.28 for the cooling mode of OC. Therefore, the random-effect model was used for TSV, and the fixed-effect model was used for OC.

3.3.1. Impact on TSV

The improvement in thermal sensation votes achieved through PCSs is a reliable indicator of their effectiveness in regulating the thermal environment [73]. Figure 5a shows the Hedges effect sizes of different HTMs of heating PCSs on occupants' thermal sensation votes. Each circle represents the mean effect size for a specific HTM or combination, along with the 95% confidence intervals (mean $\pm$ 2 S.E.). The wide confidence intervals for some combinations, particularly Cd, Cv and Rd, suggest variability in the observed effects due to a smaller amount of data. A positive effect size suggests an improvement in thermal sensation towards a more comfortable state. The variation in the size of the circles in the graph indicates the weight of each category in the analysis. The weight of a category reflects its relative contribution to the overall summary estimate, which is determined by the precision of its findings. Precision, in turn, is largely influenced by factors such as sample size and the width of the confidence interval. Larger circles representing categories contribute more to the overall effect size estimate, due to larger sample sizes or greater statistical precision. Individually, all HTMs show positive effects, with radiative devices such as radiant panels and radiative foot warmers having the largest individual impact. All the combined HTMs also demonstrate positive effects and combinations, such as Cd and Cv, with Cd, Cv and Rd especially showing larger effect sizes. In the reviewed studies, PCSs categorized as Cd and Cv included task/ambient systems, heating desks, and mats combined with fans. For Cd, Cv, and Rd, the only device identified was a warm barrel. Combined HTMs such as Cd and Rd as well as Cv and Rd showed moderate and small

effects compared to single HTMs, indicating that combining all modules might not always lead to an additive or synergistic increase in effect and that, in some cases, it could reduce the individual performances.

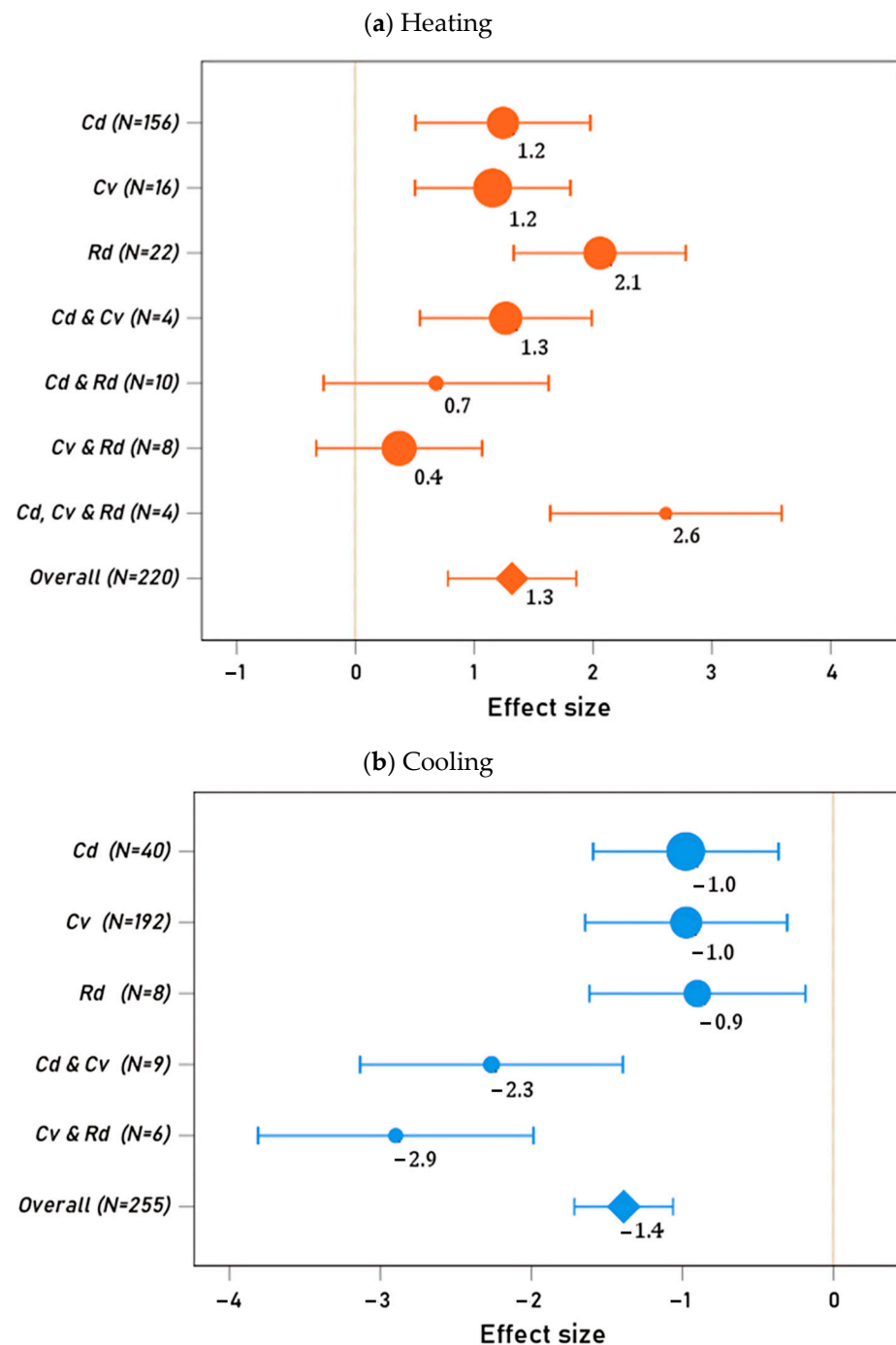


Figure 5. The Hedges effect sizes for thermal sensation vote of different heat transfer mechanisms of (a) heating and (b) cooling personal comfort systems.

Figure 5b shows the Hedges effect sizes of different HTMs of cooling PCs on occupants' thermal sensation votes. All the values show negative effects on *TSV*. This means that the effect size of PCs shifts towards the negative direction of *TSV* scale and reduces *TSV* values via cooling. The overall mean effect size of -1.4 suggests a strong overall impact. All individual HTMs show large and approximately similar effects, with *Cd* having the largest weight. As a combined HTM, *Cv* and *Rd* show the largest effect size compared

to all HTMs, indicating the potential of providing a very high *TSV* improvement toward neutral in a cooling mode.

The overall results suggest that when PCSs employ single heat transfer mechanisms, people tend to have more similar thermal sensation improvements for all the mechanisms in the cooling mode. In the heating mode, conductive and convective PCSs have similar performances, but radiative devices have a very high impact on improving thermal sensation. Employing multiple heat transfer mechanisms simultaneously in PCSs can constructively improve the cooling mode [14]; however, for some combined mechanisms, such as conduction, convection with radiation together in the heating mode [12,74], it works destructively. As an individual mechanism, radiation is best for heating PCSs, aligning with Yang et al.'s [75] findings. Conduction and convection are best suited for cooling PCSs to improve the thermal sensation, similar to Du and Ghahramani's [29] findings.

3.3.2. Impact on OC

Changes in occupant overall comfort serve as a reliable measure for evaluating the success of PCSs in providing individualized thermal regulation and comfort [9,28]. Figure 6a shows the Hedges effect sizes of different HTMs of heating PCSs on occupants' thermal sensation votes. Similar to the findings for *TSV*, the effect sizes of most HTMs on OC tend to be larger when multiple HTMs are combined, except *Cv* and *Rd*. The *Cv* and *Rd* mechanisms, as reported by Su et al. [12], were implemented through a combined convection–radiation terminal device. All of the single HTMs have a large impact, while *Rd*'s effect size is slightly lower than *Cd* and *Cv*. In combined HTMs, *Cv* and *Rd* have a moderate effect on OC, while *Cd* and *Cv* as well as *Cd* and *Rd* have large and the highest effect sizes. The results suggest that combined heat transfer mechanisms can improve OC higher than single heat transfer mechanisms. However, when multiple mechanisms are employed, effect sizes on overall comfort likely lead to more diverse results in the heating mode.

Figure 6b shows the Hedges effect sizes of different HTMs of cooling PCSs on occupants' overall comfort. Individually, all HTMs show large negative and approximately similar effects on OC, with *Rd* devices such as radiant panels having the largest individual impact. *Cd* shows a moderate effect on OC but all other HTMs show large effects. As combined HTMs, *Cv* and *Rd* devices, such as radiant desk panels with desk fans, show the largest effect sizes. These results indicate that conduction and convection have a similar effect. Conduction with radiation, as a combined mechanism, can produce a very high impact on overall comfort in the cooling mode.

Overall, the results suggest that, as individual heat transfer mechanisms, conduction and convection are better for improving overall comfort in the heating mode, aligning with Song et al.'s [9] study. In contrast, radiation-based heat transfer mechanisms are better for the cooling mode. Song et al. [9] included only a single cooling radiator dataset in their study, demonstrating a smaller effect than other mechanisms. The overall mean effect size of about 1 for both heating and cooling modes indicates that PCSs can produce a large impact on overall comfort in both modes, consistent with the findings of other reviews [8,9,29].

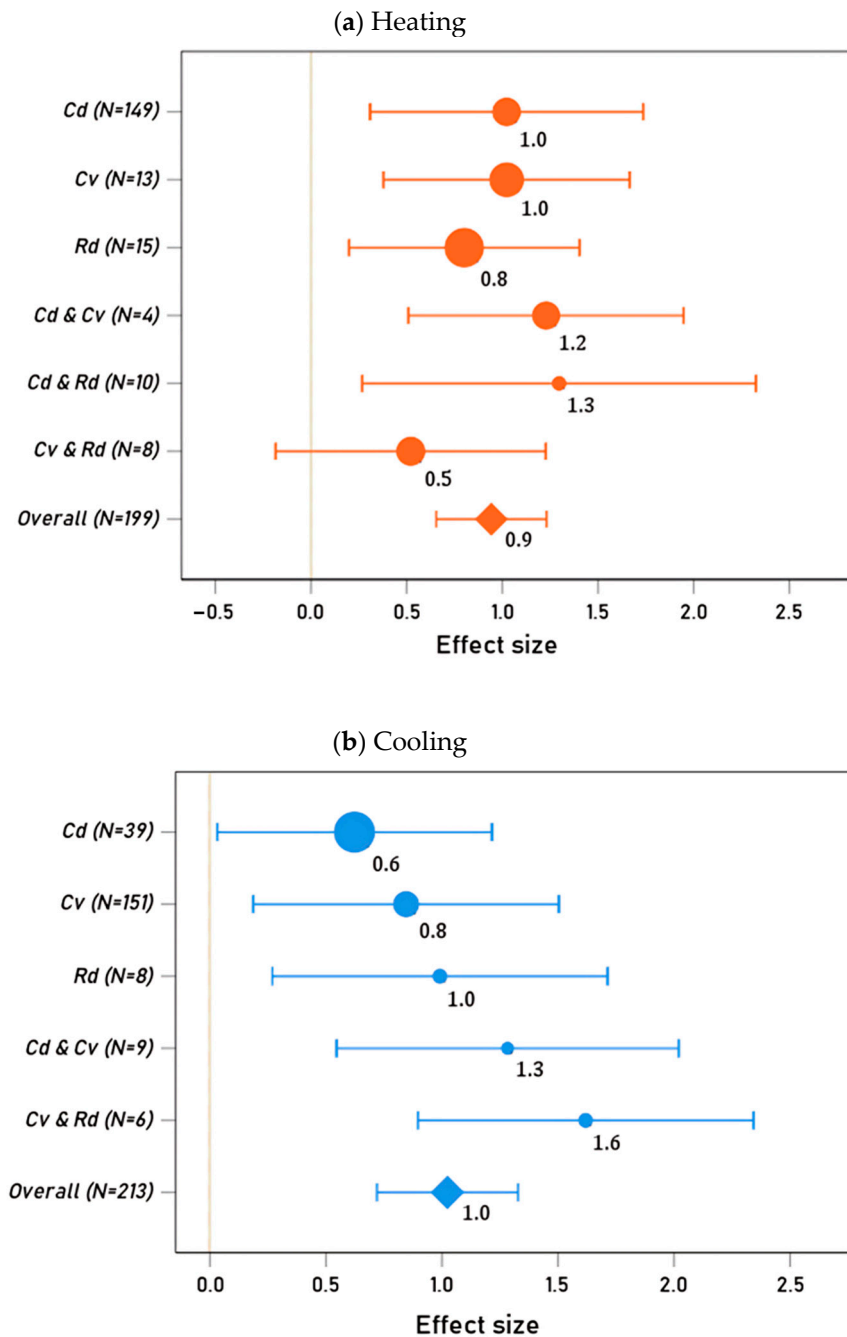


Figure 6. The Hedges effect sizes for overall comfort of different heat transfer mechanisms of (a) heating and (b) cooling personal comfort systems.

3.3.3. Relation Between *TSV* and *OC* Impact

Thermal sensation and overall comfort are highly correlated and can serve as critical indicators for validating PCS performance, as thermal perception alone may not fully represent the complex interplay of environmental and psychological factors that influence occupant satisfaction [76]. This study analyzed the correlation between the differences of *TSV* and *OC* made by PCSs to further validate findings regarding the impact of different heat transfer mechanisms on thermal perception. Table 3 shows Pearson's correlation matrix between ΔTSV and ΔOC among HTMs. Only the primary individual heat transfer mechanisms were included in the correlation analysis, as insufficient sample sizes for hybrid mechanisms precluded statistically robust evaluations. The correlation analysis between changes in *TSV* and *OC* revealed positive associations across all individual HTMs

in both heating and cooling modes, indicating that improvements in thermal sensation are closely aligned with enhanced overall comfort. These findings indicate that PCS-induced improvements in thermal sensation translate reliably into overall comfort across all individual HTMs.

Table 3. Pearson’s correlation matrix between ΔTSV and ΔOC among heat transfer mechanisms.

Heat Transfer Mechanism	Heating			Cooling		
	Number of Cases	Pearson Correlation	Sig. (2-Tailed)	Number of Cases	Pearson Correlation	Sig. (2-Tailed)
<i>Cd</i>	156	0.64	<0.001	40	0.67	<0.001
<i>Cv</i>	16	0.51	0.011	192	0.48	<0.001
<i>Rd</i>	22	0.48	0.033	8	0.74	0.037

3.4. HTMs’ Impact on Corrective Powers of PCSs

Corrective power is the difference in ambient temperature that a PCS can correct to achieve the same feeling of comfort [10,25]. This is an important indicator of the performance of PCSs, and it can be used as the metric for estimating the threshold temperature points for certain PCSs. Figure 7 demonstrates the effective extension of the perceived ambient temperature provided by different HTMs of PCSs in non-neutral environments. Conduction demonstrates robust heating performance of approximately 2.3 °C, while convection shows strong cooling results of a similar magnitude, both supported by substantial datasets that enhance statistical reliability. In heating mode, the convection and conduction combination proves most effective at approximately 3.8 °C but with considerable variability due to limited sample sizes. For cooling applications, radiation provides the smallest extension at approximately 1.1 °C, while the combined convection and radiation mechanism achieves the highest extension at approximately 3.6 °C. These findings reveal both the operational thresholds of PCS effectiveness and the inherent asymmetry between heating and cooling performances across different heat transfer mechanisms.

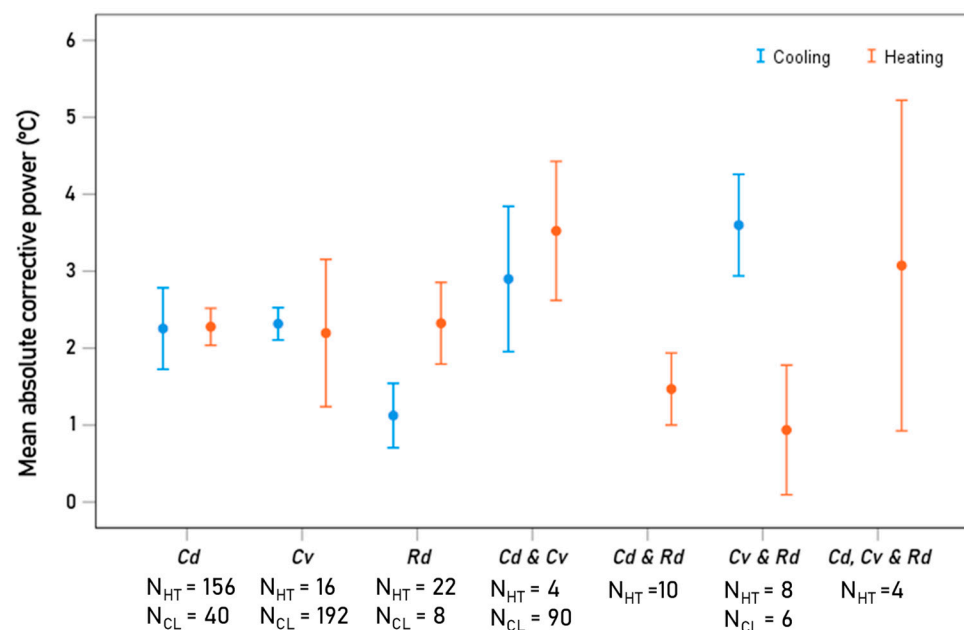


Figure 7. Corrective power values for different heat transfer mechanisms of heating and cooling personal comfort systems (N_{HT}: number of cases in heating mode; N_{CL}: number of cases in heating mode).

3.5. HTMs' Impact on Energy Performance

The energy use of PCSs is important because it can significantly reduce the energy consumption of conventional HVAC systems by conditioning only occupied zones, leading to substantial energy savings while maintaining or improving occupant comfort [9,77]. The HTM used in PCSs is crucial to energy consumption because employing more efficient modes can deliver targeted thermal comfort with significantly lower power than conventional systems [28,78]. To measure the energy consumption of a PCS by each HTM, this study analyzed the absolute *CEP* of a PCS. This metric indicates the power (W) needed to improve the 1 °C in thermal perception for a certain PCS.

Figure 8 shows the distribution of absolute *CEP* for both heating and cooling modes. The absolute *CEP* values of heating mode are generally higher and more spread out than in the cooling mode, and the amount of available data is greater in heating mode. The distributions of both modes are skewed to the right, with most values being below 100 W/°C and concentrated between 0 and 50 W/°C. This signifies that correcting thermal perception during heating typically requires more energy and is more variable in comparison to the cooling mode. In most cases, only a small amount (<100 W/°C) of energy can improve the thermal perception for both heating and cooling modes. The median *CEP* value of the heating mode is 10 times higher than that of the cooling mode. Based on the results, it can be concluded that the power consumed by PCSs to improve an individual's thermal environment is significantly lower than that of traditional HVAC systems [79,80].

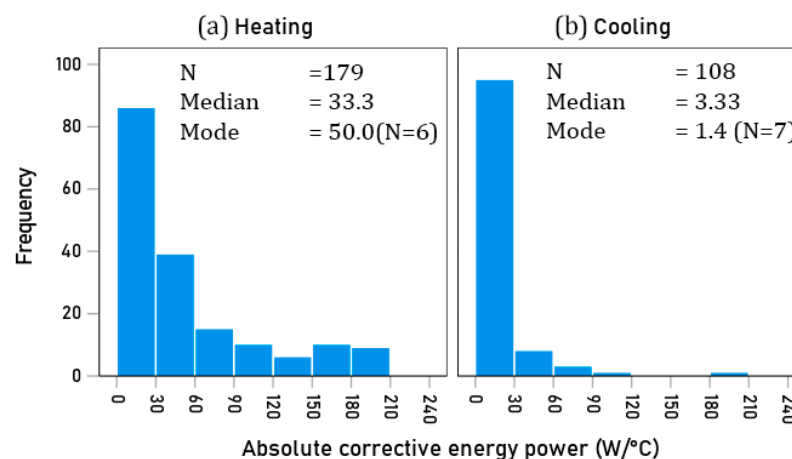


Figure 8. Distribution of absolute corrective energy power in (a) heating and (b) cooling modes.

Figure 9a displays the mean absolute *CEP* for various HTMs under heating mode. In contrast, *Cd* PCSs such as heating pads and thermal chairs exhibited the lowest mean absolute *CEP*. *Rd* as well as *Cd* and *Rd* presented intermediate mean absolute *CEP* values. These results suggest that conduction is the least power-consuming and the most efficient HTM for heating mode. Using several HTMs simultaneously can increase energy consumption; however, this can be optimized with targeted body parts and by using efficient devices, leading to high performance. Figure 9b displays the mean absolute *CEP* for various HTMs under the cooling mode. Both individual and combined HTMs exhibited a low mean absolute *CEP*, while *Cv* PCSs such as desk and stand fans showed the lowest *CEP*. The results suggest that convection is the least energy-consuming and most efficient HTM for the cooling mode. According to *Cd* and *Cv* data, using several HTMs simultaneously has not considerably increased energy consumption in the cooling mode.

Considering both heating and cooling modes, the absolute *CEP* tends to be higher for most of the HTMs of heating compared to cooling. Most of the mean absolute *CEPs* are below 200 W/°C for both heating and cooling modes, as found in Rugani et al. [78],

Song et al. [9], and Tang et al. [81]. Findings suggest that, generally, many heat transfer mechanisms of PCSs consume more energy to modify thermal perception in the heating mode than in the cooling mode. The most energy-efficient heat transfer mechanism for cooling mode comprises convection-based PCSs, such as fans. Conduction-based PCSs, such as heating pads and chairs, are most energy-efficient in heating mode. Considering both comfort and energy performance, according to the results of this meta-analysis, convection-based mechanisms for cooling mode and conduction-based mechanisms can be recommended to PCSs for achieving maximum comfort and energy savings.

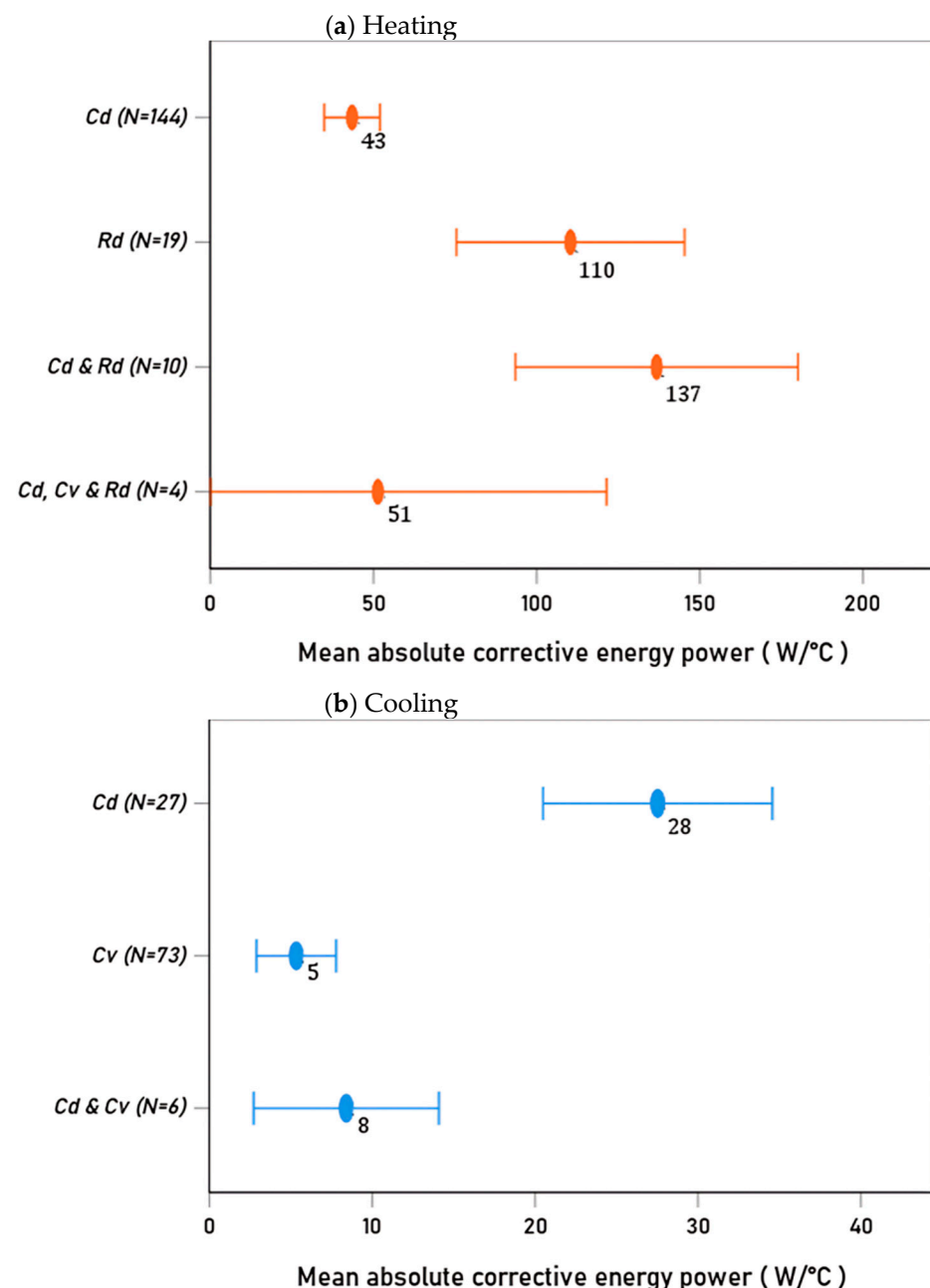


Figure 9. Mean absolute CEP and 95% confidence interval (mean $\pm$ 2 S.E.) for different HTMs of (a) heating and (b) cooling PCSs (with data with sample sizes below four being excluded from the figure).

4. Overall Discussion and Future Work

This meta-analysis examined how different HTMs in PCSs influence thermal comfort and energy efficiency. The review of 64 PCS studies revealed an unequal distribution of HTMs, with conduction and convection being the most studied, while radiation and

combined HTMs received limited attention. Although many studies did not report PCS power consumption values, the reported ranges varied considerably, from 0.6 to 630 W. PCSs employed three primary heat transfer mechanisms (conductive, convective, and radiant) tailored to provide heating or cooling to the subject. Physiological targeting reveals strategic preferences for head/neck regions primarily through convective cooling, while extremities and torso applications demonstrate regional differentiation between heating and cooling strategies. Multi-zone hybrid approaches increasingly combine complementary thermal interventions to address complex human thermoregulatory requirements.

PCSs effectively improve perceptual responses by shifting thermal sensation and overall comfort values by about one scale unit toward neutrality in both heating and cooling modes. This indicates reduced discomfort and enhanced comfort without significantly altering individual variability, indicating that using PCSs is an effective strategy for improving thermal comfort and enabling energy savings through HVAC setpoint adjustments. However, integrating PCSs with existing HVAC systems can be complex, often increasing related installation and maintenance costs. Their effectiveness largely depends on users' understanding and behavior, with the risk that misoperation may reduce efficiency or cause discomfort to others [8,16]. The results highlight distinct performance trends across HTMs. Radiative systems emerge as the most effective for improving thermal sensations in heating, while conductive and convective mechanisms are more effective in cooling. Hybrid systems, such as conduction with convection, consistently enhance overall comfort compared with single mechanisms, though their evidence base remains limited. The correlation analysis between thermal sensations and overall comfort confirmed strong positive associations across all single heat transfer mechanisms, validating that PCS-induced thermal improvements translate reliably into enhanced occupant comfort. The corrective power analysis revealed significant asymmetries in PCS performance, with conduction and convection demonstrating robust individual performance of approximately 2.3 °C in heating and cooling modes, respectively, supported by substantial datasets. Combined heat transfer mechanisms showed enhanced potential, particularly the convection–conduction combination in heating and convection–radiation in cooling. These results establish operational thresholds for different heat transfer mechanisms in PCS applications. Notably, the energy efficiency of conduction in heating and convection in cooling are robust compared to other available HTMs. Importantly, conclusions remain tentative on convection in heating and conduction in cooling, due to the under-representations of studies and hybrid HTMs.

The performance matrix (Figure 10) reveals distinct trade-offs between thermal comfort and energy efficiency across different heat transfer mechanisms. Conduction consistently demonstrates balanced performance, delivering moderate improvements in both *TSV* and *OC* with relatively low *CEP* values in both heating and cooling modes, establishing it as the most energy-efficient option. Convection produces comparable comfort effects with significantly lower *CEP* in cooling mode. Convection in heating mode and radiation in cooling mode remain inconclusive due to insufficient data availability. Radiation demonstrates promising thermal improvements in heating applications, while combined mechanisms, particularly the *Cd*, *Cv* and *Rd* configuration, indicate potential for enhanced comfort delivery, though these hybrid systems should be considered tentative, given the limited sample sizes and absent *OC* data. Overall, conduction-based systems demonstrate the most reliable balance between comfort enhancement and energy performance across both operational modes, while convective PCSs are most suited for cooling modes.

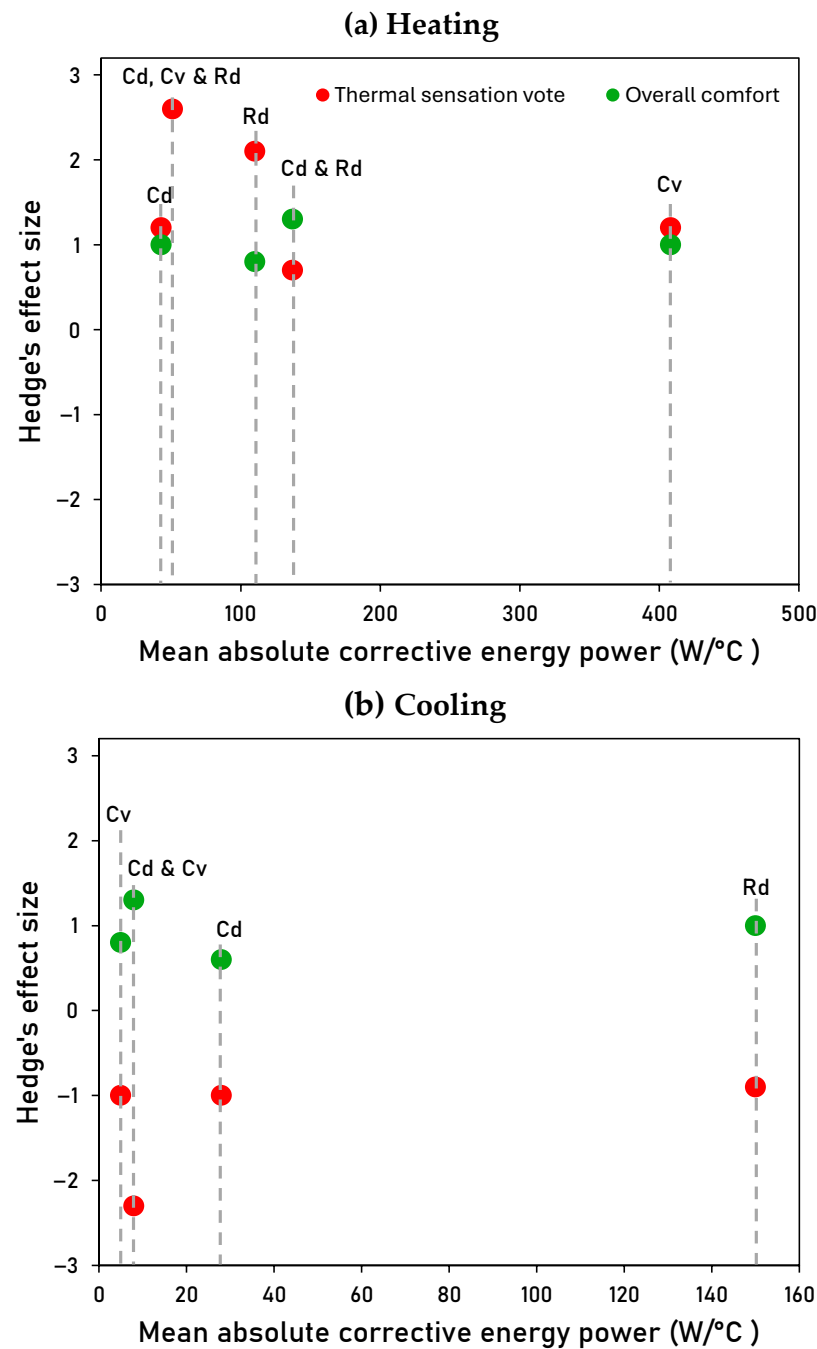


Figure 10. Relation between corrective energy power and Hedges effect sizes in (a) heating and (b) cooling modes. Note: *CEP* values for convection in the heating mode and radiation in the cooling mode should be considered tentative due to the limited sample size ($N = 2$ for *Cv* in HT and *Rd* in CL).

For the heating mode, Tang et al. [81] identified *Cd* (heated cushion) as the most effective HTM for OC improvement, followed by *Cv* and *Rd*. For *TSV*, *Cv* was the most effective, followed by *Cd* and *Rd*. However, Yang et al. [75] indicated that *Rd* (radiant heater, leg warmer and firebox) was more effective for OC improvement, whereas *Cv* was more effective for *TSV* enhancement. Another study suggested that *Rd* was the most effective HTM, followed by *Cv* and *Cd* [82]. Additionally, studies demonstrated that the high-power *Rd* mechanism could exceed *Cd*'s performance, while the *Cd* mechanism was more effective than the *Cv* mechanism in heating PCSs [27].

For the cooling mode, other studies have identified Cv as a highly effective HTM, particularly when fan-assisted airflow was employed. Cv significantly enhanced heat dissipation to the surrounding air. Rd was found to be effective in facilitating heat exchange when the body temperature exceeded the ambient temperature. In contrast, Cd heat transfer was observed to be the least effective when applied alone, as it relied on direct contact with surfaces and influenced only limited areas of the body [6]. However, conduction-based PCSs, such as thermoelectric cooling chairs, neck coolers, thermoelectric heat pump modules, and cooling pads, are effective but slightly more energy-consuming than other HTMs in the cooling mode. The variability in various studies emphasizes that Cd , Cv and Rd can significantly improve the thermal comfort of occupants in various contexts, and that the impact of HTM varies. This may be the effect of the contact area of the body and the targeted body part [4,83].

However, energy efficiency varies significantly: Cd is the most efficient for heating, requiring the least power for comfort improvement. This advantage stems from direct heat transfer through physical contact, which minimizes thermal losses compared to convective or radiative heating methods. Cv is optimal for cooling due to its low energy demand, and the reason for this may be the effectiveness of air flow in influencing the heat loss via evaporation. Generally, CEP values for heating PCSs are higher than cooling PCSs, similar to the findings of Song et al. [9]. Li et al. [84] found that Cd has the highest energy efficiency with the lowest CEP , followed by Rd and Cv among convective, conductive and radiative heating devices, similar to this study's findings. These findings highlight the importance of selecting the optimal HTM based on the cooling or heating mode to achieve comfort with energy savings.

Apart from the technical performance of different HTMs, the effectiveness of PCSs in practice is strongly shaped by user behavior and adoption. Correct positioning, adjustment of intensity, and consistent use are essential for achieving intended comfort and energy savings, whereas misoperation may offset benefits or even cause discomfort to others. Behavioral factors, such as clothing insulation, posture, and movement, can also influence PCS performance and interact differently with HTMs. For example, thick clothing can reduce the effectiveness of conductive heating or cooling chairs, while limited body-surface contact from one's posture may weaken conductive performance, suggesting that radiative or convective methods may be preferable in such cases. Adoption is further influenced by usability and perceived intrusiveness, which ultimately determines whether PCSs achieve widespread energy savings. These considerations highlight the need for user-centered design and behavioral support to ensure that technological potential translates into practical benefits.

Although certain HTM categories included a limited number of studies, they were retained in this meta-analysis because Hedges' effect size is bias-corrected for small samples, and their inclusion ensures a comprehensive comparison across PCS types. However, categories with fewer than four cases were excluded from the CEP analysis, as such small sample sizes could overly skew the results and lack statistical significance. Findings related to radiation in the cooling mode, convection in the heating mode, and hybrid PCSs should be interpreted cautiously due to the limited number of studies available. While these categories showed promising trends, further evidence is required before drawing definitive conclusions about their relative performance.

Despite these insights, this study has limitations. In this study, PCS devices were classified based on their primary HTM, while acknowledging potential secondary influences. However, this approach may not fully capture the overall HTM effects of some devices, representing a limitation of the analysis. Limited data were available for combined HTMs in PCSs, and the existing data across different HTMs were unevenly distributed. This might

limit the robustness of comparisons among HTMs. Most of the studies were conducted in climate chambers. This will limit the real-world application of our findings. However, Sun et al. [85] reported no significant performance differences between climate chamber and field experiments, though real-world settings may allow for greater comfort gains through adaptive behaviors [86]. Many studies have not been precise and have not clearly outlined the power consumption of the PCS devices that were used within them. This reliance on subjective comfort metrics (*TSV*, *OC*) with varying scales in this study may limit the insights we obtained from other metrics, such as *PMV*, skin temperature, and ambient temperature. Considerable heterogeneity in study designs, such as differences in devices and experimental protocols, further complicates interpretation, requiring random-effect models. High-power devices were excluded from the *CEP* analysis to avoid bias. While this may narrow the scope and limit the representation of certain emerging technologies, exclusion can be justified as these devices were the only cases exhibiting outlying behavior compared to the power values of other devices. Limited exploration of combined HTMs restricts our understanding of potential interactions. Additionally, reliance on a fixed Griffiths' constant ($G = 0.33$) in *CEP* calculations may not capture individual differences in thermal perception. However, Rijal et al. [87] showed that near the neutral *TSV* value, different Griffiths' constants (0.25, 0.33, 0.50) have a negligible impact, which aligns with this study's mean *TSV*, which is near zero. Most included studies are from Asia, where cultural and climatic factors may affect PCS performance [88,89]. However, Wang et al. [90] argued that comfort preferences mainly depend on local climate and building types. Further research is needed to clarify the regional effects on PCS outcomes. These limitations suggest that conclusions should be interpreted cautiously and highlight the need for larger, field-based studies using standardized performance metrics to strengthen the evidence base.

Future work should focus on standardizing PCS performance metrics, conducting real-world validations, and exploring adaptive PCSs that dynamically adjust HTMs for personalized comfort. Additionally, more studies are needed to optimize hybrid systems, such as *Cd* and *Rd* or *Cv* and *Rd*, to maximize both comfort and efficiency. Specifically, studies on convective heating and radiative cooling PCSs can help address gaps in the literature. By addressing these gaps, future PCS designs can better integrate multiple HTMs, improving user satisfaction while minimizing energy consumption in both heating and cooling applications. This study found that radiation is highly effective in providing comfort; therefore, future work can focus on developing energy-efficient radiation devices for both heating and cooling modes. PCS studies can focus on the contact surface area of PCS and targeted body parts with different HTMs for identifying relations and optimal strategies for energy savings with maximum comfort.

Beyond identifying conduction as efficient for heating and convection for cooling, the findings can inform specific PCS design and integration strategies. For example, conduction-based PCSs, such as heated cushions or thermoelectric chairs, can be paired with central HVAC systems during heating seasons to reduce the overall supply air temperature while still ensuring occupant comfort. Similarly, convection-based PCSs, like task fans or ventilated chairs, can complement HVAC cooling by enabling higher cooling setpoints, thereby reducing chiller loads. Radiation-based PCSs, though under-studied, show promise for targeted applications, such as radiant desk panels or under-desk heaters, which can reduce reliance on whole-room heating. Future PCS design could benefit from hybrid systems—such as conductive seating combined with low-power fans that dynamically adjust operation based on occupant demand—offering a pathway to both energy savings and enhanced comfort in real-world HVAC-integrated environments.

5. Conclusions

This study conducted a comprehensive meta-analysis of 64 studies to evaluate how different heat transfer mechanisms (HTMs) influence the thermal comfort and energy performance of personal comfort systems (PCSs). By systematically analyzing conduction (Cd), convection (Cv), and radiation (Rd) mechanisms in both heating and cooling modes, this research study provides key insights for optimizing PCS design. The findings demonstrate that the strategic selection of HTMs can significantly enhance occupant comfort while improving the energy efficiency in buildings. The main conclusions of this meta-analysis are summarized below.

1. PCSs improve thermal sensations and overall comfort by approximately 1 scale unit in both heating and cooling modes. Hence, PCSs are effective in enhancing occupant comfort across both heating and cooling modes.
2. The highest impactful individual heat transfer mechanism for both heating and cooling modes was Rd . Among the combined mechanisms, the highest impactful heat transfer mechanism was the Cd and Cv mechanism. The least effective individual heat transfer mechanism was Cv for heating and Cd for cooling. Combined mechanisms have performed constructively in the cooling mode, but the Cv and Rd mechanism has the lowest impact in the heating mode. Hybrid heat transfer mechanisms in PCSs should be applied judiciously, as the system's effectiveness depends on selecting mode-specific mechanisms. For maximizing occupant comfort, radiative heat transfer is the most effective when used individually for both heating and cooling.
3. Most of the PCSs consumed less energy ($<200 \text{ W}/^\circ\text{C}$) to improve thermal perception in both modes while most of the HTMs in the heating mode had higher CEP values compared to the cooling mode. Cd for heating and Cv for cooling are recommended as the most comfort-improving and energy-efficient HTMs.

The key findings of this study suggest that PCSs improve occupant comfort by about one scale unit in both heating and cooling modes. Radiative heat transfer is the most effective individual mechanism; hybrid methods should be applied carefully. Most PCSs operate efficiently with conductive heating and convective cooling, offering an optimal balance between comfort and energy savings. The uneven distribution of data across different heat transfer mechanisms, particularly for combined mechanisms, underscores the need for more studies to be carried out on multiple heat transfer mechanisms in order for us to understand their impact on PCS performance better. Future studies should focus on optimal HTMs for the design of PCSs. Focusing on improving the energy efficiency of high-comfort, produceable HTMs such as radiative methods and combined HTMs can be helpful in achieving maximum comfort while also achieving energy savings. In future designs, conduction mechanisms should be incorporated into heating PCSs, while cooling PCS could utilize convective mechanisms to enhance comfort and promote energy sustainability in buildings.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Summary of previous studies.

Reference	Type	Targeted Body Parts	Mode	Heat Transfer Method	Number of Subjects	Power Values (W)
Zhai et al. [91]	Floor fan	Head/face/neck, arms/wrists/hands, torso	CL	Cv	16	2.8, 3.3, 4.8, 5.7, 7.9, 10.3
Huang et al. [92]	Frontal desk fan	Head/face/neck, arms/wrists/hands, torso	CL	Cv	30	-
Cui and Cao [93]	Fan simulated natural wind/constant mechanical wind	Head/face/neck, arms/wrists/hands, torso	CL	Cv	18	-
Arens et al. [94]	Opposing air jets	Head/face/neck	CL	Cv	18	-
Attahajariyakul and Lertsatittanakorn [95]	Desk fan	Head/face/neck	CL	Cv	15	-
Zhang and Zhao [96]	Local airflow	Head/face/neck	CL	Cv	30	-
Amai et al. [97]	Task conditioning system/personal environmental module/under-desk task unit/remote control unit/remote control unit + mesh four terminal devices	Head/face/neck, arms/wrists/hands, front/back torso	CL	Cv	24	-
Zhai et al. [98]	Ceiling fan	Head/face/neck, arms/wrists/hands, front/back torso	CL	Cv	16	-
Kubo et al. [99]	Uniform airflow on whole body	Front of whole body	CL	Cv	4, 9, 8, 6	-
Zhang et al. [15]	Foot warmer	Head/face/neck, L=legs/feet	HT	Rd	12	11, 5
Watanabe et al. [100]	Cooling chair	Back of torso, buttocks	CL	Cv	7	-
Brooks and Parsons [101]	Heated seat	Back of torso, buttocks	HT	Cd	8	-
Su et al. [12]	Convection and radiation combined terminal device: Fixed/User control	Head/face/neck, legs/feet, front torso	HT	Cv and Rd	16	-
Shahzad et al. [102]	Thermal chair	Back of torso, buttocks	HT	Cd	44	-
Du et al. [43]	Local warm air supplier: Supply air temperature 32, 42, 52, 28, 34, 40, 26, 30, 34, 22 °C	Legs/feet	HT	Cv	20	-
Zhu et al. [27]	Radiant panel (low/high)/heating plate/fan heater	Legs/feet	HT	$Rd/Cd/Cv$	20	230, 170, 450, 230

Table A1. Cont.

Reference	Type	Targeted Body Parts	Mode	Heat Transfer Method	Number of Subjects	Power Values (W)
Song et al. [14]	Hybrid personal cooling garment	Front/back torso, buttocks	CL	Cd and Cv	11	-
Verhaart et al. [103]	Personalized air movement: 23, 26 °C supply temperature	Head/face/neck	CL	Cv	12	-
Kaczmarczyk et al. [104]	Personal ventilation supply temperature 21, 26 °C	Head/face/neck	CL	Cv	32	-
Li et al. [44]	Foot heating pad—constant heating 30 W, 90 W, high and low fluctuating frequency heating	Legs/feet	HT	Cd	16	52, 56, 60
Pasut et al. [65]	Ceiling fan: 2/3 oscillating/fixed front/side/below	Head/face/neck, arms/wrists/hands, front/back torso	CL	Cv	16	2, 3
Luo et al. [13]	Heating desk, heating mat and ventilation fans	Head/face/neck, arms/wrists/hands, front torso, legs/feet	HT	Cd and Cv	18	-
Tang et al. [81]	Warm air blower/radiant heater/heated cushion/desk/floor fan, ventilated cushion	Head/face/neck, arms/wrists/hands, front/back torso, legs/feet	HT/CL	$Cv/Cd/Rd$	28	3.3, 10.1, 29.9, 43, 420, 630
Lee et al. [105]	Ventilation seat/cold water seat/electric heating/hot water	Back of torso, buttocks	CL/HT	Cv	20	-
Pallubinsky et al. [106]	Face cooling/back cooling/foot sole cooling/face underarm cooling	Head/face/neck	CL	Cv	16	-
Veselý et al. [23]	Heated chair/desk mat/floor mat/combination: user controlled/fixed/automated	Arms/wrists/hands, back torso, buttocks, legs/feet	HT	Cd	13	36, 80, 100, 216
Udayraj et al. [107]	Radiant heating panel with table pad/heated chair with heated floor mattress/heated jacket and heated trousers/radiant heating panel with table pad	Arms/wrists/hands, front/back torso, buttocks, legs/feet	HT	Rd and Cd/Cd	14	16, 133, 325
Yang et al. [66]	Footwarmer normal shoes/sandals	Legs/feet	HT	Rd	32	125
Wang et al. [108]	Radiant/wrist/ankle/torso/combined heating	Face, torso, ankles, wrists/hands	HT	Rd/Cd	20	450, 16, 20, 60, 36, 80, 76
Song et al. [109]	Electrically heated/chemically ensemble	Torso and legs	HT	Cd	8	15.9
Tang et al. [110]	Cooling air towards the breathing zone/chest and back/combined	Face and torso	CL	Cv	28	-

Table A1. Cont.

Reference	Type	Targeted Body Parts	Mode	Heat Transfer Method	Number of Subjects	Power Values (W)
Zhao et al. [111]	Ventilation cooling shirt	Torso	CL	Cv	8	-
He et al. [11]	Radiant cooling desk/local airflow: 1.6, 2.2 m/s/combined	Head/face/neck, arms/wrists/hands, front torso	CL	$Rd/Cv/Rd$ and Cv (Cd *)	20	2, 3
Verhaart et al. [112]	Personalized air movement: Supply temperature 23, 25, 26 °C,	Head/face/neck	CL	Cv	11	-
Yu et al. [113]	Heated floor panel and insulated chair	Arms/wrists/hands, legs/feet	HT	Cd	10	30
Yang al. [74]	Table pad, backrest, cushion heaters, and leg warmer	Arms/wrists/hands, back torso, buttocks, legs/feet	HT	Cd and Rd	8	145
Kimmling and Hoffmann [67]	Thermoelectric cooling partition 50, 100% cooling power	Head, lower/upper body from side	CL	Rd	7	60
Sun et al. [114]	Displacement ventilation system	Whole body	CL	Cv	32	23
He et al. [115]	Desk fan 1.5, 2.3 m/s, user controlled	Head/face/neck	CL	Cv	24	0.8, 1.5, 1.8, 2, 3
Ren et al. [116]	Heating plates 1–4/2–4	Legs/feet	HT	Rd	20	156.5, 170.1, 208.4, 226.8
Li et al. [63]	Under-floor air distribution 22.18 °C + personalized ventilation 26.22 °C: 5/10 L/s	Face and whole body	CL	Cv	30	-
Akimoto et al. [117]	Task ambient system	Whole body	CL	Cv	20	-
Schiavon et al. [45]	Stand fan	Face and upper body from side	CL	Cv	56	4, 7.6
He et al. [46]	Radiant cooling desk	Upper body, hand, wrist	CL	Rd (Cd *)	20	-
Wang et al. [108]	Local heating floor mat small/large—low/high power	Feet	HT	Cd	16	60, 110
Oi et al. [59]	Seat/foot warmer/combined	Back torso, buttocks, Legs/feet	HT	Cd	8	10, 48, 58
He et al. [24]	Retrofitted Huotong	Buttocks, legs, whole body	HT	Cd , Cv , and Rd	16	49.4, 104.1, 140.3, 165.7
Yang et al. [118]	Heated chair equipped with backrest and seat-heating cushions	Back torso and buttocks	HT	Cd	13	90
He et al. [60]	Heating chair/heating chair with leg warmer	Back torso, buttocks, legs	HT	Cd	12	19.4, 25.3, 25.4, 34.1, 34.9, 41.1
Pasut et al. [119]	Heated/cooled chair + cover/clothing/fan	Back torso, buttocks	HT/CL	Cd	23	3.6, 16
Zhang et al. [68]	Task/ambient conditioning (TAC) system	Face/head, legs/feet, hands/wrists/palms	HT/CL	Cd , Cd and Cv	18	59,41,
Luo et al. [10]	Heating insoles/wrist pad/chair heating/combined/fan/chair cooling/combined	Feet/leg, buttocks, back torso, hand, wrists, face	HT/CL	$Cd/Cv/Cv$ and Cd	20	2.4, 7, 9.4, 16.4, 21, 23.4, 4.4, 5.6, 8

Table A1. Cont.

Reference	Type	Targeted Body Parts	Mode	Heat Transfer Method	Number of Subjects	Power Values (W)
Pasut et al. [120]	Thermoelectric chair	Back torso and buttocks	HT/CL	<i>Cd</i>	30	42, 74
Yang et al. [61]	Back, buttocks, combined cooling	Back torso and buttocks	CL	<i>Cd</i>	16	54.5, 54.8, 66.2, 61.9, 64.6, 83.2, 72.5, 73.3, 97.7
He et al. [121]	Desk fans/desk fans+ air conditioning	Face and upper body	CL	<i>Cv</i>	16	0.7, 1.1, 1.2, 1.4, 1.9, 2.2, 2.4, 2.9
Ke et al. [122]	Nanoporous polyethylene clothing	Front/back torso, arms	CL	<i>Cd</i>	18	-
H Yang et al. [123]	Chest/abdomen/upper back/lower back cooling	Front and back torso	CL	<i>Cd</i>	20	45
Udayraj et al. [64]	Ventilation clothing/desk fan	Torso cooling, forehead/hand cooling	CL	<i>Cv</i>	14	5.2, 40
Liu et al. [52]	Neck cooler, fan	Neck/face/head	CL	<i>Cd, Cv</i>	14	-
Wu et al. [124]	Fan	Head/face/hands	CL	<i>Cv</i>	12	3
Ilmiawan et al. [125]	Fan: Different directions	Face/head/upper body	CL	<i>Cv</i>	20	15
Wu et al. [126]	Heating pad with and without air condition	Front/back torso, feet	HT	<i>Cd</i>	12	20.9
Yang et al. [82]	Wristband, leg band, insole, warm air blower, radiant heater, combined heating	Wrist, legs, feet	HT	<i>Cd</i>	26	4, 5, 10, 19
Belyamani et al. [62]	Thermoelectric heat pump module	Upper back torso	CL	<i>Cd</i>	60	8

–: not available; UC: user controlled; CL: cooling; HT: heating; *Cd*: conduction; *Cv*: convection; *Rd*: radiation; (*): not directly mentioned in this study but may have a significant effect.

Table A2. Amount of data included for this study for each heat transfer mechanism.

Heat Transfer Mechanism (HTM)	TSV		OC		CEP	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
<i>Cd</i>	156	40	149	39	144	27
<i>Cv</i>	16	192	13	151	2	73
<i>Rd</i>	22	8	15	8	19	2
<i>Cd</i> and <i>Cv</i>	4	9	4	9	-	6
<i>Cd</i> and <i>Rd</i>	10	-	10	-	10	-
<i>CV</i> and <i>Rd</i>	8	6	8	6	-	-
<i>Cd, Cv</i> and <i>Rd</i>	4	-	-	-	4	-
Total	220	255	199	213	179	108

TSV: thermal sensation vote; OC: overall comfort; CEP: corrective energy power; *Cd*: conduction; *Cv*: convection; *Rd*: radiation.

References

1. Tanaka, N. Technology roadmap energy-efficient buildings: Heating and cooling equipment. *Int. Energy Agency* **2011**, *5*, 6–8.
2. Simulation-Based Control for Energy Efficiency Building Operation and Maintenance—European Commission. Available online: <https://cordis.europa.eu/project/id/608981/reporting/de> (accessed on 19 March 2025).
3. Kim, J.; Bauman, F.; Raftery, P.; Arens, E.; Zhang, H.; Fierro, G.; Anderson, M.; Culler, D. Occupant comfort and behavior: High-resolution data from a 6-month field study of personal comfort systems with 37 real office workers. *Build. Environ.* **2019**, *148*, 348–360. [\[CrossRef\]](#)
4. Luo, W.; Kramer, R.; De Kort, Y.; Van Marken Lichtenbelt, W. Effectiveness of personal comfort systems on whole-body thermal comfort—A systematic review on which body segments to target. *Energy Build.* **2022**, *256*, 111766. [\[CrossRef\]](#)
5. Personal Comfort Systems Study Collects Data to Better Predict Occupant Thermal Comfort | Ashrae.org. Available online: <https://www.ashrae.org/news/ashraejournal/personal-comfort-systems-study-collects-data-to-better-predict-occupant-thermal-comfort> (accessed on 30 April 2025).
6. Enescu, D. Heat transfer mechanisms and contributions of wearable thermoelectrics to personal thermal management. *Energies* **2024**, *17*, 285. [\[CrossRef\]](#)
7. Tian, M.; Jiang, Q. Personal thermal management strategies to reduce energy consumption: Principles and applications of new materials with bionic structures. *Energy Build.* **2024**, *324*, 114887. [\[CrossRef\]](#)
8. Rawal, R.; Schweiker, M.; Kazanci, O.B.; Vardhan, V.; Jin, Q.; Duanmu, L. Personal comfort systems: A review on comfort, energy, and economics. *Energy Build.* **2020**, *214*, 109858. [\[CrossRef\]](#)
9. Song, W.; Zhang, Z.; Chen, Z.; Wang, F.; Yang, B. Thermal comfort and energy performance of personal comfort systems (PCS): A systematic review and meta-analysis. *Energy Build.* **2022**, *256*, 111747. [\[CrossRef\]](#)
10. Luo, M.; Arens, E.; Zhang, H.; Ghahramani, A.; Wang, Z. Thermal comfort evaluated for combinations of energy-efficient personal heating and cooling devices. *Build. Environ.* **2018**, *143*, 206–216. [\[CrossRef\]](#)
11. He, Y.; Li, N.; Wang, X.; He, M.; He, D. Comfort, energy efficiency and adoption of personal cooling systems in warm environments: A field experimental study. *Int. J. Environ. Res. Public Health* **2017**, *14*, 1408. [\[CrossRef\]](#)
12. Su, W.; Yang, B.; Zhou, B.; Wang, F.; Li, A. A novel convection and radiation combined terminal device: Its impact on occupant thermal comfort and cognitive performance in winter indoor environments. *Energy Build.* **2021**, *246*, 111123. [\[CrossRef\]](#)
13. Luo, W.; Kramer, R.; Kort, Y.; Rense, P.; Marken Lichtenbelt, W. 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* **2022**, *32*, e12951. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Song, W.; Wang, F.; Wei, F. Hybrid cooling clothing to improve thermal comfort of office workers in a hot indoor environment. *Build. Environ.* **2016**, *100*, 92–101. [\[CrossRef\]](#)
15. Zhang, H.; Arens, E.; Taub, M.; Dickerhoff, D.; Bauman, F.; Fountain, M.; Pasut, W.; Fannon, D.; Zhai, Y.; Pigman, M. Using footwarmers in offices for thermal comfort and energy savings. *Energy Build.* **2015**, *104*, 233–243. [\[CrossRef\]](#)
16. Exss, K.; Wegertseder-Martínez, P.; Trebilcock, M. A systematic review of Personal Comfort Systems from a post-phenomenological view. *Ergonomics* **2025**, *68*, 163–186. [\[CrossRef\]](#)
17. Ryu, J.; Kim, J. Effect of different HVAC control strategies on thermal comfort and adaptive behavior in high-rise apartments. *Sustainability* **2021**, *13*, 11767. [\[CrossRef\]](#)
18. Lala, B.; Biju, A.; Vanshita Rastogi, A.; Dahiya, K.; Kala, S.M.; Hagishima, A. The challenge of multiple thermal comfort prediction models: Is TSV enough? *Buildings* **2023**, *13*, 890. [\[CrossRef\]](#)
19. Sun, T.; Luo, A.; Lu, Y.; Zhen, M.; Zhang, Y.; Bian, G. Research on indoor thermal comfort of orthopedic patients in hospital. *Sci. Rep.* **2025**, *15*, 9053. [\[CrossRef\]](#)
20. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). *ASHRAE Handbook: Fundamentals*; ASHRAE: Atlanta, GA, USA, 2009.
21. Xue, J.; Hu, X.; Sani, S.N.; Wu, Y.; Li, X.; Chai, L.; Li, D. Outdoor thermal comfort at a university campus: Studies from personal and long-term thermal history perspectives. *Sustainability* **2020**, *12*, 9284. [\[CrossRef\]](#)
22. Zhang, D.; Hou, H.; Tsang, T.W.; Mui, K.W.; Wong, L.T. Predicting students' thermal sensation votes in university libraries taking into account their mood states. *Indoor Built Environ.* **2024**, *33*, 859–875. [\[CrossRef\]](#)
23. Veselý, M.; Molenaar, P.; Vos, M.; Li, R.; Zeiler, W. Personalized heating—Comparison of heaters and control modes. *Build. Environ.* **2017**, *112*, 223–232. [\[CrossRef\]](#)
24. He, Y.; Li, N.; Zhou, L.; Wang, K.; Zhang, W. Thermal comfort and energy consumption in cold environment with retrofitted Huotong (warm-barrel). *Build. Environ.* **2017**, *112*, 285–295. [\[CrossRef\]](#)
25. Zhang, H.; Arens, E.; Zhai, Y. A review of the corrective power of personal comfort systems in non-neutral ambient environments. *Build. Environ.* **2015**, *91*, 15–41. [\[CrossRef\]](#)
26. Huang, T.; Wang, M.; Feng, S.; Peng, Z.; Huang, X.; Song, Y. Study on the coupled heat transfer of conduction, convection, and radiation in foam concrete based on a microstructure numerical model. *Buildings* **2024**, *14*, 1287. [\[CrossRef\]](#)

27. Zhu, X.; Liu, H.; He, M.; Wu, Y.; Xiong, F.; Li, B. Comparing the improvement of occupant thermal comfort with local heating devices in cold environments. *Build. Environ.* **2025**, *268*, 112350. [\[CrossRef\]](#)
28. Xu, X.; Zhang, H.; Schiavon, S.; Lian, Z.; Parkinson, T.; Lo, J.C. The effects of personal comfort systems on sleep: A systematic review. *Renew. Sustain. Energy Rev.* **2025**, *213*, 115474. [\[CrossRef\]](#)
29. Du, H.; Ghahramani, A. Evaluating personal comfort systems performance—A design of experiments based review. *Build. Environ.* **2025**, *283*, 113415. [\[CrossRef\]](#)
30. Lin, L.; Aloe, A.M. Evaluation of various estimators for standardized mean difference in meta-analysis. *Stat. Med.* **2021**, *40*, 403–426. [\[CrossRef\]](#)
31. Marfo, P.; Okyere, G.A. The accuracy of effect-size estimates under normals and contaminated normals in meta-analysis. *Heliyon* **2019**, *5*, e01838. [\[CrossRef\]](#)
32. Cao, Y.; Xie, K. Mature but nascent—A scoping review for wearable thermoregulating devices. *Energy Build.* **2024**, *318*, 114438. [\[CrossRef\]](#)
33. Warthmann, A.; Wölki, D.; Metzmacher, H.; Van Treeck, C. Personal climatization systems—A review on existing and upcoming concepts. *Appl. Sci.* **2018**, *9*, 35. [\[CrossRef\]](#)
34. Shahzad, S.; Calautit, J.K.; Calautit, K.; Hughes, B.; Aquino, A.I. Advanced personal comfort system (APCS) for the workplace: A review and case study. *Energy Build.* **2018**, *173*, 689–709. [\[CrossRef\]](#)
35. Sen, S.; Yildirim, I. A Tutorial on how to conduct meta-analysis with IBM SPSS Statistics. *Psych* **2022**, *4*, 640–667. [\[CrossRef\]](#)
36. LabPlot—Scientific Plotting and Data Analysis. Available online: <https://labplot.org/> (accessed on 30 April 2025).
37. Yang, W.; Moon, H.J.; Jeon, J.Y. Comparison of response scales as measures of indoor environmental perception in combined thermal and acoustic conditions. *Sustainability* **2019**, *11*, 3975. [\[CrossRef\]](#)
38. Schweiker, M.; Fuchs, X.; Becker, S.; Shukuya, M.; Dovjak, M.; Hawighorst, M.; Kolarik, J. Challenging the assumptions for thermal sensation scales. *Build. Res. Inf.* **2017**, *45*, 572–589. [\[CrossRef\]](#)
39. Pantavou, K.; Koletsis, I.; Lykoudis, S.; Melas, E.; Nikolopoulou, M.; Tsiros, I.X. Native influences on the construction of thermal sensation scales. *Int. J. Biometeorol.* **2020**, *64*, 1497–1508. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Humphreys, M.A.; Nicol, J.F.; Raja, I.A. Field studies of indoor thermal comfort and the progress of the adaptive approach. *Adv. Build. Energy Res.* **2007**, *1*, 55–88. [\[CrossRef\]](#)
41. Humphreys, M.; Nicol, F.; Roaf, S. *Adaptive Thermal Comfort: Foundations and Analysis*, 1st ed.; Routledge: Oxfordshire, UK, 2015.
42. Zhang, Y.; Zhao, R. Overall thermal sensation, acceptability and comfort. *Build. Environ.* **2008**, *43*, 44–50. [\[CrossRef\]](#)
43. Du, C.; Liu, H.; Li, C.; Xiong, J.; Li, B.; Li, G.; Xi, Z. Demand and efficiency evaluations of local convective heating to human feet and low body parts in cold environments. *Build. Environ.* **2020**, *171*, 106662. [\[CrossRef\]](#)
44. Li, Q.; Liu, H.; Wu, Y.; Kosonen, R.; Li, B. Effects of constant and fluctuating temperature modes of foot heating on human thermal responses in cold environments. *Build. Environ.* **2023**, *238*, 110364. [\[CrossRef\]](#)
45. Schiavon, S.; Yang, B.; Donner, Y.; Chang, V.W.C.; Nazaroff, W.W. Thermal comfort, perceived air quality, and cognitive performance when personally controlled air movement is used by tropically acclimatized persons. *Indoor Air* **2017**, *27*, 690–702. [\[CrossRef\]](#)
46. He, Y.; Li, N.; He, M.; He, D. Using radiant cooling desk for maintaining comfort in hot environment. *Energy Build.* **2017**, *145*, 144–154. [\[CrossRef\]](#)
47. Hedges, L.V. Distribution theory for glassf s estimator of effect size and related estimators. *J. Educ. Stat.* **1981**, *6*, 107–128. [\[CrossRef\]](#)
48. Lakens, D. Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for *t*-tests and ANOVAs. *Front. Psychol.* **2013**, *4*, 863. [\[CrossRef\]](#)
49. Melsen, W.G.; Bootsma, M.C.J.; Rovers, M.M.; Bonten, M.J.M. The effects of clinical and statistical heterogeneity on the predictive values of results from meta-analyses. *Clin. Microbiol. Infect.* **2014**, *20*, 123–129. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Buck, R.J.; Fieberg, J.; Larkin, D.J. The use of weighted averages of Hedges' d in meta-analysis: Is it worth it? *Methods Ecol. Evol.* **2022**, *13*, 1093–1105. [\[CrossRef\]](#)
51. Hedges, L.V.; Olkin, I. *Statistical Methods for Meta-Analysis*; Academic Press: Cambridge, MA, USA, 1985.
52. Liu, L.; Xin, J.; Liu, Z.; Zeng, W.; Li, Q.; Jin, L.; You, R.; Liu, M.; Liu, H. Are wearable local cooling devices effective in Chinese residential kitchens during hot summer? *Build. Environ.* **2024**, *257*, 111532. [\[CrossRef\]](#)
53. Wang, Z.; Warren, K.; Luo, M.; He, X.; Zhang, H.; Arens, E.; Chen, W.; He, Y.; Hu, Y.; Jin, L.; et al. Evaluating the comfort of thermally dynamic wearable devices. *Build. Environ.* **2020**, *167*, 106443. [\[CrossRef\]](#)
54. Fanger, P.O. *Thermal Comfort: Analysis and Applications in Environmental Engineering*; Danish Technical Press: Copenhagen, Denmark, 1970; 244p.
55. Rupp, R.F.; Parkinson, T.; Kim, J.; Toftum, J.; De Dear, R. The impact of occupant's thermal sensitivity on adaptive thermal comfort model. *Build. Environ.* **2022**, *207*, 108517. [\[CrossRef\]](#)

56. Rupp, R.F.; Kim, J.; Ghisi, E.; de Dear, R. Thermal sensitivity of occupants in different building typologies: The Griffiths constant is a variable. *Energy Build.* **2019**, *200*, 11–20. [\[CrossRef\]](#)
57. Cao, W.; Xuan, X.; Wang, Y.; Wu, W. The thermal sensitivity (Griffiths constant) of occupants for naturally ventilated buildings in China. *Energy Build.* **2025**, *341*, 115786. [\[CrossRef\]](#)
58. Tartarini, F.; Schiavon, S.; Cheung, T.; Hoyt, T. CBE Thermal comfort tool: Online tool for thermal comfort calculations and visualizations. *SoftwareX* **2020**, *12*, 100563. [\[CrossRef\]](#)
59. Oi, H.; Yanagi, K.; Tabata, K.; Tochihiro, Y. Effects of heated seat and foot heater on thermal comfort and heater energy consumption in vehicle. *Ergonomics* **2011**, *54*, 690–709. [\[CrossRef\]](#) [\[PubMed\]](#)
60. He, Y.; Wang, X.; Li, N.; He, M.; He, D. Heating chair assisted by leg-warmer: A potential way to achieve better thermal comfort and greater energy conservation in winter. *Energy Build.* **2018**, *158*, 1106–1116. [\[CrossRef\]](#)
61. Yang, H.; Deng, Y.; Cao, B.; Zhu, Y. Study on the local and overall thermal perceptions under nonuniform thermal exposure using a cooling chair. *Build. Environ.* **2020**, *176*, 106864. [\[CrossRef\]](#)
62. Belyamani, M.A.; Hurley, R.F.; Djamasbi, S.; Somasse, G.B.; Strauss, S.; Zhang, H.; Smith, M.J.; Dessel, S.V.; Liu, S. Local wearable cooling may improve thermal comfort, emotion, and cognition. *Build. Environ.* **2024**, *254*, 111367. [\[CrossRef\]](#)
63. Li, R.; Sekhar, S.C.; Melikov, A.K. Thermal comfort and IAQ assessment of under-floor air distribution system integrated with personalized ventilation in hot and humid climate. *Build. Environ.* **2010**, *45*, 1906–1913. [\[CrossRef\]](#)
64. Udayraj Li, Z.; Ke, Y.; Wang, F.; Yang, B. Personal cooling strategies to improve thermal comfort in warm indoor environments: Comparison of a conventional desk fan and air ventilation clothing. *Energy Build.* **2018**, *174*, 439–451. [\[CrossRef\]](#)
65. Pasut, W.; Arens, E.; Zhang, H.; Zhai, Y. Enabling energy-efficient approaches to thermal comfort using room air motion. *Build. Environ.* **2014**, *79*, 13–19. [\[CrossRef\]](#)
66. Yang, B.; Li, Z.; Zhou, B.; Olofsson, T.; Li, A. Enhanced effects of footwarmer by wearing sandals in winter office: A Swedish case study. *Indoor Built Environ.* **2021**, *30*, 875–885. [\[CrossRef\]](#)
67. Kimmling, M.; Hoffmann, S. Preliminary study of thermal comfort in buildings with PV-powered thermoelectric surfaces for radiative cooling. *Energy Procedia* **2017**, *121*, 87–94. [\[CrossRef\]](#)
68. Zhang, H.; Arens, E.; Kim, D.; Buchberger, E.; Bauman, F.; Huizenga, C. Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system. *Build. Environ.* **2010**, *45*, 29–39. [\[CrossRef\]](#)
69. Aqilah, N.; Rijal, H.B.; Zaki, S.A. A Review of thermal comfort in residential buildings: Comfort threads and energy saving potential. *Energies* **2022**, *15*, 9012. [\[CrossRef\]](#)
70. Peddie, K.M.; Soligo, M.J. Holistic approach to human comfort. *Aust. J. Multi Discip. Eng.* **2020**, *16*, 20–30. [\[CrossRef\]](#)
71. Lian, Z. Revisiting thermal comfort and thermal sensation. *Build. Simul.* **2024**, *17*, 185–188. [\[CrossRef\]](#)
72. Hoyt, T.; Arens, E.; Zhang, H. Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. *Build. Environ.* **2015**, *88*, 89–96. [\[CrossRef\]](#)
73. Wang, Z.; Zhang, Y.; Xia, Y.; Chen, X.; Liu, J. Study on personal comfort heating system and human thermal comfort in extremely low-temperature building environments. *Build. Environ.* **2024**, *259*, 111640. [\[CrossRef\]](#)
74. Yang, B.; Wu, M.; Li, Z.; Yao, H.; Wang, F. Thermal comfort and energy savings of personal comfort systems in low temperature office: A field study. *Energy Build.* **2022**, *270*, 112276. [\[CrossRef\]](#)
75. Yang, Z.; Zhang, W.; Liu, H.; Zhang, W.; Qin, M. Field study of meeting thermal needs of occupants in old residential buildings in low-temperature environments using personalized local heating. *Build. Environ.* **2024**, *247*, 111004. [\[CrossRef\]](#)
76. Jing, W.; Qin, Z.; Mu, T.; Ge, Z.; Dong, Y. Evaluating thermal comfort indices for outdoor spaces on a university campus. *Sci. Rep.* **2024**, *14*, 21253. [\[CrossRef\]](#) [\[PubMed\]](#)
77. Zhang, J.; Zhou, X.; Lei, S.; Luo, M. Energy and comfort performance of occupant-centric air conditioning strategy in office buildings with personal comfort devices. *Build. Simul.* **2022**, *15*, 899–911. [\[CrossRef\]](#)
78. Rugani, R.; Bernagozzi, M.; Picco, M.; Salvadori, G.; Marengo, M.; Zhang, H.; Fantozzi, F. Thermal comfort and energy efficiency evaluation of a novel conductive-radiative personal comfort system. *Build. Environ.* **2023**, *244*, 110787. [\[CrossRef\]](#)
79. Yasuhiko, K.; Akinobu, M.; Kimiko, Y.; Kazuhiko, S.; Weisheng, Z. Study on electricity consumption for domestic refrigerators, air conditioners, and water dispenser in Guangzhou (China) urban area based on questionnaire data. *J. Jpn. Inst. Energy* **2011**, *90*, 554–561. [\[CrossRef\]](#)
80. Yoshida, A.; Hoang, T.N.; Tasaki, T. Household survey on air conditioner use and energy consumption in Vietnam. *Glob. Environ. Res.* **2021**, *25*, 75–84.
81. Tang, Y.; Yu, H.; Zhang, K.; Niu, K.; Mao, H.; Luo, M. Thermal comfort performance and energy-efficiency evaluation of six personal heating/cooling devices. *Build. Environ.* **2022**, *217*, 109069. [\[CrossRef\]](#)
82. Yang, Y.; Shi, N.; Zhang, R.; Zhou, H.; Ding, L.; Tao, J.; Zhang, N.; Cao, B. Study on the effect of local Heating devices on human thermal comfort in low-temperature built environment. *Buildings* **2024**, *14*, 3996. [\[CrossRef\]](#)
83. Cheng, Y.; Niu, J.; Gao, N. Thermal comfort models: A review and numerical investigation. *Build. Environ.* **2012**, *47*, 13–22. [\[CrossRef\]](#)

84. Li, S.; Jia, X.; Peng, C.; Zhu, Y.; Cao, B. Thermal comfort benefits, energy efficiency, and occupant regulation behaviour in four types of personal heating within the built environment. *Build. Environ.* **2024**, *266*, 112075. [\[CrossRef\]](#)
85. Sun, H.; Yang, Z.; Lin, B.; Shi, W.; Zhu, Y.; Zhao, H. Comparison of thermal comfort between convective heating and radiant heating terminals in a winter thermal environment: A field and experimental study. *Energy Build.* **2020**, *224*, 110239. [\[CrossRef\]](#)
86. Kubota, T.; Rijal, H.B.; Takaguchi, H. (Eds.) *Sustainable Houses and Living in the Hot-Humid Climates of Asia*; Springer: Berlin/Heidelberg, Germany, 2018.
87. Rijal, H.B.; Humphreys, M.A.; Nicol, J.F. Adaptive model and the adaptive mechanisms for thermal comfort in Japanese dwellings. *Energy Build.* **2019**, *202*, 109371. [\[CrossRef\]](#)
88. Draganova, V.; Tsuzuki, K.; Nabeshima, Y. Field study on nationality differences in thermal comfort of university students in dormitories during winter in Japan. *Buildings* **2019**, *9*, 213. [\[CrossRef\]](#)
89. Havenith, G.; Griggs, K.; Qiu, Y.; Dorman, L.; Kulasekaran, V.; Hodder, S. Higher comfort temperature preferences for anthropometrically matched Chinese and Japanese versus white-western-middle-European individuals using a personal comfort/cooling system. *Build. Environ.* **2020**, *183*, 107162. [\[CrossRef\]](#)
90. Wang, Z.; Zhang, H.; He, Y.; Luo, M.; Li, Z.; Hong, T.; Lin, B. Revisiting individual and group differences in thermal comfort based on ASHRAE database. *Energy Build.* **2020**, *219*, 110017. [\[CrossRef\]](#)
91. Zhai, Y.; Zhang, H.; Zhang, Y.; Pasut, W.; Arens, E.; Meng, Q. Comfort under personally controlled air movement in warm and humid environments. *Build. Environ.* **2013**, *65*, 109–117. [\[CrossRef\]](#)
92. Huang, L.; Ouyang, Q.; Zhu, Y.; Jiang, L. A study about the demand for air movement in warm environment. *Build. Environ.* **2013**, *61*, 27–33. [\[CrossRef\]](#)
93. Cui, W.; Cao, G.; Ouyang, Q.; Zhu, Y. Influence of dynamic environment with different airflows on human performance. *Build. Environ.* **2013**, *62*, 124–132. [\[CrossRef\]](#)
94. Arens, E.; Zhang, H.; Pasut, W.; Warneke, A.; Bauman, F. *Thermal Comfort and Perceived Air Quality of a PEC System*; Proceedings of Indoor Air: Austin, TX, USA, 2011.
95. Atthajariyakul, S.; Lertsatittanakorn, C. Small fan assisted air conditioner for thermal comfort and energy saving in Thailand. *Energy Convers. Manag.* **2008**, *49*, 2499–2504. [\[CrossRef\]](#)
96. Zhang, Y.; Zhao, R. Relationship between thermal sensation and comfort in non-uniform and dynamic environments. *Build. Environ.* **2009**, *44*, 1386–1391. [\[CrossRef\]](#)
97. Amai, H.; Tanabe Sichi Akimoto, T.; Genma, T. Thermal sensation and comfort with different task conditioning systems. *Build. Environ.* **2007**, *42*, 3955–3964. [\[CrossRef\]](#)
98. Zhai, Y.; Zhang, Y.; Zhang, H.; Pasut, W.; Arens, E.; Meng, Q. Human comfort and perceived air quality in warm and humid environments with ceiling fans. *Build. Environ.* **2015**, *90*, 178–185. [\[CrossRef\]](#)
99. Kubo, H.; Isoda, N.; Enomoto-Koshimizu, H. Cooling effects of preferred air velocity in muggy conditions. *Build. Environ.* **1997**, *32*, 211–218. [\[CrossRef\]](#)
100. Watanabe, S.; Shimomura, T.; Miyazaki, H. Thermal evaluation of a chair with fans as an individually controlled system. *Build. Environ.* **2009**, *44*, 1392–1398. [\[CrossRef\]](#)
101. Brooks, J.E.; Parsons, K.C. An ergonomics investigation into human thermal comfort using an automobile seat heated with encapsulated carbonized fabric (ECF). *Ergonomics* **1999**, *42*, 661–673. [\[CrossRef\]](#) [\[PubMed\]](#)
102. Shahzad, S.; Calautit, J.K.; Aquino, A.I.; Nasir, D.S.; Hughes, B.R. Neutral thermal sensation or dynamic thermal comfort? Numerical and field test analysis of a thermal chair. *Energy Procedia* **2017**, *142*, 2189–2194. [\[CrossRef\]](#)
103. Verhaart, J.; Quaas, L.; Li, R.; Zeiler, W. Comfort of cooling by personal air movement. 14th International Conference on Indoor Air Quality and Climate. *Indoor Air* **2016**, *2016*, 1–9.
104. Kaczmarczyk, J.; Melikov, A.; Sliva, D. Effect of warm air supplied facially on occupants' comfort. *Build. Environ.* **2010**, *45*, 848–855. [\[CrossRef\]](#)
105. Lee, M.; Shin, Y.; Lee, H.; Cho, H. Investigation of bio-signal changes of occupants resting in buildings using local cooling and heating seats. *Energy Build.* **2021**, *245*, 111092. [\[CrossRef\]](#)
106. Pallubinsky, H.; Schellen, L.; Rieswijk, T.A.; Breukel, C.M.G.A.M.; Kingma, B.R.M.; Van Marken Lichtenbelt, W.D. Local cooling in a warm environment. *Energy Build.* **2016**, *113*, 15–22. [\[CrossRef\]](#)
107. Udayraj Li, Z.; Ke, Y.; Wang, F.; Yang, B. A study of thermal comfort enhancement using three energy-efficient personalized heating strategies at two low indoor temperatures. *Build. Environ.* **2018**, *143*, 1–14. [\[CrossRef\]](#)
108. Wang, H.; Xu, M.; Bian, C. Experimental comparison of local direct heating to improve thermal comfort of workers. *Build. Environ.* **2020**, *177*, 106884. [\[CrossRef\]](#)
109. Song, W.; Wang, F.; Zhang, C.; Lai, D. On the improvement of thermal comfort of university students by using electrically and chemically heated clothing in a cold classroom environment. *Build. Environ.* **2015**, *94*, 704–713. [\[CrossRef\]](#)
110. Tang, J.; Liu, Y.; Du, H.; Lan, L.; Sun, Y.; Wu, J. The effects of portable cooling systems on thermal comfort and work performance in a hot environment. *Build. Simul.* **2021**, *14*, 1667–1683. [\[CrossRef\]](#)

111. Zhao, M.; Kuklane, K.; Lundgren, K.; Gao, C.; Wang, F. A ventilation cooling shirt worn during office work in a hot climate: Cool or not? *Int. J. Occup. Saf. Ergon.* **2015**, *21*, 457–463. [[CrossRef](#)] [[PubMed](#)]
112. Verhaart, J.; Li, R.; Zeiler, W. User interaction patterns of a personal cooling system: A measurement study. *Sci. Technol. Built Environ.* **2018**, *24*, 57–72. [[CrossRef](#)]
113. Yu, G.; Gu, Z.; Yan, Z.; Chen, H. Investigation and comparison on thermal comfort and energy consumption of four personalized seat heating systems based on heated floor panels. *Indoor Built. Environ.* **2021**, *30*, 1252–1267. [[CrossRef](#)]
114. Sun, W.; Cheong, K.W.D.; Melikov, A.K. Subjective study of thermal acceptability of novel enhanced displacement ventilation system and implication of occupants' personal control. *Build. Environ.* **2012**, *57*, 49–57. [[CrossRef](#)]
115. He, M.; Li, N.; He, Y.; He, D.; Song, C. The influence of personally controlled desk fan on comfort and energy consumption in hot and humid environments. *Build. Environ.* **2017**, *123*, 378–389. [[CrossRef](#)]
116. Ren, Z.; Gao, X.; Xiao, Y.; Liu, Y. Thermal comfort and energy conservation of a four-sided enclosed local heating device in a cold environment. *Build. Environ.* **2023**, *228*, 109837. [[CrossRef](#)]
117. Akimoto, T.; Tanabe Sichi Yanai, T.; Sasaki, M. Thermal comfort and productivity—Evaluation of workplace environment in a task conditioned office. *Build. Environ.* **2010**, *45*, 45–50. [[CrossRef](#)]
118. Yang, H.; Cao, B.; Zhu, Y. Study on the effects of chair heating in cold indoor environments from the perspective of local thermal sensation. *Energy Build.* **2018**, *180*, 16–28. [[CrossRef](#)]
119. Pasut, W.; Zhang, H.; Arens, E.; Zhai, Y. Energy-efficient comfort with a heated/cooled chair: Results from human subject tests. *Build. Environ.* **2015**, *84*, 10–21. [[CrossRef](#)]
120. Pasut, W.; Zhang, H.; Arens, E.; Kaam, S.; Zhai, Y. Effect of a heated and cooled office chair on thermal comfort. *HVACR Res.* **2013**, *19*, 574–583. [[CrossRef](#)]
121. He, Y.; Li, N.; Li, N.; Li, J.; Yan, J.; Tan, C. Control behaviors and thermal comfort in a shared room with desk fans and adjustable thermostat. *Build. Environ.* **2018**, *136*, 213–226. [[CrossRef](#)]
122. Ke, Y.; Wang, F.; Xu, P.; Yang, B. On the use of a novel nanoporous polyethylene (nanoPE) passive cooling material for personal thermal comfort management under uniform indoor environments. *Build. Environ.* **2018**, *145*, 85–95. [[CrossRef](#)]
123. Yang, H.; Cao, B.; Ju, Y.; Zhu, Y. The effects of local cooling at different torso parts in improving body thermal comfort in hot indoor environments. *Energy Build.* **2019**, *198*, 528–541. [[CrossRef](#)]
124. Wu, Y.; Fan, J.; Cao, B. Comparison among different modeling approaches for personalized thermal comfort prediction when using personal comfort systems. *Energy Build.* **2023**, *285*, 112873. [[CrossRef](#)]
125. Ilmiawan, F.A.; Zaki, S.A.; Singh, M.K.; Khalid, W. Effect of preferable wind directions on personal thermal comfort of occupants in the air-conditioned office in hot-humid climate. *Build. Environ.* **2024**, *254*, 111390. [[CrossRef](#)]
126. Wu, J.; Liu, J.; Zhao, J.; Su, Y. Influencing assessment of different heating modes on thermal comfort in electric vehicle cabin. *Energy Built Environ.* **2024**, *5*, 556–567. [[CrossRef](#)]

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