

Article

A Contrast Experiment on the Ventilation Direction towards Human Head in Personalized Environmental Control System (PECS)

Canyang Li, Wenkai Fu and Xi Meng *

Innovation Institute for Sustainable Maritime Architecture Research and Technology (ISMART),
Qingdao University of Technology, Qingdao 266033, China; conyonoba@126.com (C.L.);
qutfuwenkai@163.com (W.F.)

* Correspondence: mengxihvac@163.com

Abstract: A heating, ventilation, and air-conditioning system is designed for the entire space but falls short in meeting diverse individual needs. Therefore, the personalized environmental control system is proposed to address individual thermal requirements and it has been widely accepted and produced to have significant practical value for humans. In order to enhance the comfort level based on the PECS, the impact of the airflow direction towards the head in terms of physiological and psychological sensations was investigated. Different airflow directions were considered as follows: front blowing (FB-PV), side blowing (SB-PV), back blowing (BB-PV), top blowing (TB-PV), and a control group No-PV. A total of 56 participants were invited to assess the thermal environment, and their skin temperature was measured. The results revealed that the airflow towards the head improved thermal comfort and reduced the mean skin temperature by 0.4–0.6 °C, with FB-PV showing particularly promising results. TB-PV demonstrated the highest level of comfort with a score of +1.05 (slightly higher than “Just comfortable (+1)”) and scored significantly higher in overall willingness at +1.21 (higher than “Willing (+1)”). Conversely, FB-PV resulted in a discomfort level due to restricted breathing under the continuous airflow condition.

Keywords: personalized environmental control system; airflow direction; thermal comfort; human head



Citation: Li, C.; Fu, W.; Meng, X. A Contrast Experiment on the Ventilation Direction towards Human Head in Personalized Environmental Control System (PECS). *Sustainability* **2024**, *16*, 5704. <https://doi.org/10.3390/su16135704>

Academic Editor: Marco Noro

Received: 31 May 2024

Revised: 1 July 2024

Accepted: 2 July 2024

Published: 3 July 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

With the swift pace of urbanization and the continual expansion of building footprints, a considerable surge in energy consumption during building operations has been witnessed [1,2]. The energy consumption within the construction industry represents more than 40% of China’s overall energy consumption, and heating, ventilation, and air-conditioning (HVAC) systems, utilized in buildings, make up roughly 47% of the operational energy usage [3]. HVAC systems function as the principal mechanism for controlling indoor thermal settings, endeavoring to elevate indoor thermal comfort. Nevertheless, these systems have encountered critique owing to their substantial energy consumption and their role in exacerbating air pollution [4]. Consequently, diminishing energy usage for air-conditioning and heating purposes proves advantageous in mitigating society’s overall energy consumption.

The quality of indoor environments stands as a pivotal factor in determining residents’ health. Accordingly, buildings often incorporate HVAC systems to regulate indoor temperatures and introduce fresh outdoor air, meeting the environmental requirements of indoor occupants [5]. However, substantial divergence exists in the subjective perception of thermal environments among different populations [6–8]. Indoor environments suitable for certain individuals might be unsuitable for others, highlighting HVAC systems’ incapacity to meet personalized needs. Therefore, systems that accommodate individual differences are deemed a potential solution to address this issue [9–11].

In pursuit of better thermal comfort for indoor occupants, scholars introduced the concept of task ambient conditioning (TAC) systems [9], which can regulate localized thermal environments, aiding in reducing the surrounding environment's intensity requirements, decreasing energy consumption, and offering a comfortable and healthy environment [12]. Subsequently, the personalized environmental control system (PECS) emerged as a further advancement of TAC [9]. The PECS coordinates individual control systems and centralized building management systems, optimizing service delivery where required, thereby bringing substantial energy efficiency and heightened user satisfaction [13]. It not only needs to consider thermal comfort, but also provide clean, cool, and fresh air to occupants. Currently, numerous types of personal environmental control devices for heating or cooling have been developed. They have been widely used in floors [14], desktops [15], partitions [16,17], and ceilings [18]. Meanwhile, the PECS is typically used to concentrate control on the microenvironment around occupants, or settings targeting the torso, head, and even the breathing zone [19].

Personalized ventilation (PV), as a personalized environmental control technology, has garnered extensive adoption and demonstrates significant impacts on individuals. PV directly delivers fresh air to individuals according to their preferences [19]. Each component in PV can be independently controlled, allowing individuals to adjust relevant parameters according to their preferences. Previous studies [20] have identified a wide range of parameters related to PV control, such as airflow temperature [21], airflow speed [22], and air quality [23], thereby improving health and productivity [24], notably in systems where desktop systems dominate personalized ventilation [25,26]. Hence, PV plays a crucial role in improving comfort, air quality, and energy efficiency [23,27,28].

Human comfort is greatly impacted by surrounding air movements [29–31]. Individuals exposed to different air speeds can experience thermal comfort despite different warm conditions [30]. Typically, as the air temperature increases, people tend to favor higher air velocities. Previous studies suggest that different airflow directions affecting the human body produce diverse effects [32]. Airflow directed towards the body's front over shorter distances is more prone to draft sensation, whereas airflow from a ceiling fan is generally better received [33]. In their study examining dissatisfaction rates related to airflow directed towards the body from various directions, Toftum et al. [34] found that dissatisfaction rates were highest with airflow from below at air temperatures of 20 °C and 23 °C. Nonetheless, research on the impact of airflow direction on human perception and comfort is still limited. Hence, conducting further analysis to determine differences in thermal perception and comfort resulting from airflow from various directions on the human body is necessary and viable.

Diverse regions of the human body demonstrate varied sensitivities to thermal stimuli, both heat and cold [35]. In a consistent environmental context, localized stimulation can elicit markedly different thermal sensations across various body parts. The head, particularly the forehead, exhibits a heightened sensitivity to thermal changes in comparison to other body regions [36]. Although the skin temperature of the head is less affected by environmental fluctuations, its cooling can notably enhance the body's overall thermal regulation [37,38]. The head's increased blood flow facilitates more efficient heat exchange, establishing it as a pivotal site for body heat dissipation [39]. Yang et al. [40] indicated that head cooling not only improves thermal acceptability among occupants but also increases the upper limit of tolerable indoor temperatures. Stevens et al. [41] revealed that the facial region, especially near the mouth, is particularly sensitive to cold stimuli. Cotter et al. [42] found that the thermal sensitivity of the head and face to localized cooling is 2–5 times greater compared to other body parts. Additionally, directing personalized airflow towards the head serves to deliver conditioned fresh air directly to the breathing zone, effectively averting the circulation of stale or polluted air within an enclosed environment.

While PV systems have been shown to enhance thermal comfort, indoor air quality, and energy efficiency, a more detailed analysis of their impact on human thermal comfort, especially for specific body parts such as the head, is currently lacking. When employing

PV systems for convective heat exchange, the human head is highly sensitive to airflow, and its thermal sensation significantly influences overall bodily comfort. High-speed and continuous airflow directed towards the breathing zone may cause discomfort symptoms, such as dry eyes. Altering the direction of airflow acting on the head may potentially address this issue. Based on this premise, a contrast experiment was conducted, considering four airflow directions: front blowing (FB-PV), side blowing (SB-PV), back blowing (BB-PV), and top blowing (TB-PV) towards the human head. Among them, “Side blowing” refers to directing airflow to the participants’ heads from the left side only. (Our preliminary investigation revealed no significant differences in participants’ subjective physiological and psychological feelings between left-side and right-side airflow. Therefore, for the convenience of platform setup, we consistently directed airflow to the left side of the participants’ heads). A total of 56 participants were invited to assess the thermal environment under different airflow directions while concurrently monitoring their skin temperatures. The objectives and novelty of this study are as follows:

- Investigate the changes in skin temperature and thermal and airflow sensation before and after exposure to airflow directed at the head.
- Analyze the impact of airflow direction towards the head on human comfort through comparative experiments.

2. Research Methodology

2.1. Description of Experimental Platform

The experiment was conducted in Qingdao city, China, during summer 2023, from 4–6 PM daily in rainless weather, and the experimental room had dimensions of 3.0 m (length) $\times$ 3.0 m (width) $\times$ 2.8 m (height), equipped with an air-conditioning system and a humidifier device. The air-conditioning system was installed near the exterior wall at a height of 2.5 m above the ground, while the humidifier’s nozzle was approximately 1.0 m high. Throughout the experiment, the indoor temperature and relative humidity were maintained at a constant level of 29.0 ± 0.5 °C and $60 \pm 5\%$, respectively. To mitigate the impact of solar radiation on the indoor air temperature, the window was covered with black curtains during the experiment. Then, to minimize the interference from natural ventilation, all doors and windows were closed to ensure that the indoor air speed remained below 0.15 m/s.

Table 1 lists the designed and measured parameters under experimental conditions. Figure 1 illustrates both the schematic diagram and photograph of the platform. As depicted, the system comprised a ventilator, a flexible air duct, an airflow control valve, an adjustable air outlet, as well as other auxiliary support components. The direction and position of the air outlet could be freely adjusted to meet specific airflow requirements. Meanwhile, an armless chair was used with adjustable height, aligning their heads with the air outlet to enhance subjective perception accuracy. The air outlet was aligned with the head of the subject, and in all four directions, it was kept about 50 cm away from the skin.

Table 1. Designed and measured environmental parameters (mean value $\pm$ standard deviation).

	Air Temperature	Relative Humidity	Airflow Speed around Subjects	Room Air Speed
Designed	29.0 ± 0.5 °C	$60 \pm 5\%$	1.80 ± 0.15 m/s	<0.15 m/s
Measured	29.1 ± 0.2 °C	$58 \pm 3\%$	1.84 ± 0.11 m/s	0.11 ± 0.03 m/s

The comfort zone in the ASHRAE standard sets an upper air speed limit of 0.8 m/s in a warm environment. However, numerous existing experiments [31,43,44] have shown that achieving thermal comfort in warm environments requires an air speed exceeding 0.8 m/s, indicating that the ASHRAE standard underestimates occupant airflow requirements. Therefore, based on the existing literature and data, in this experiment, the airflow speed near the human head was maintained at a moderate to high speed of approximately 1.8 m/s

by controlling the control valve, allowing for a better evaluation of the impact of airflow direction on perception.

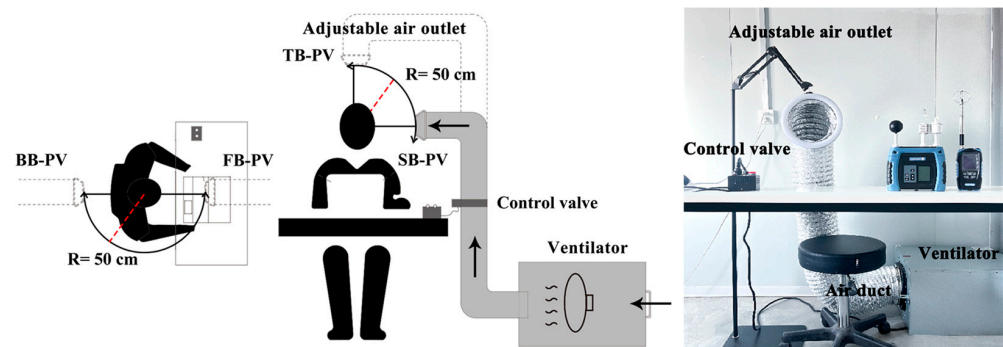


Figure 1. A schematic diagram and photograph of the platform.

2.2. Description of Experimental Procedure

In this study, five groups were performed simultaneously: FB-PV, SB-PV, BB-PV, TB-PV, and no personalized ventilation (No-PV). No-PV status indicated the shutdown of the system and served as the control group, representing the comparison with the four experimental groups. The skin temperature measurement and questionnaire survey were employed to assess the influence of airflow direction. Figure 2 shows the experimental process.

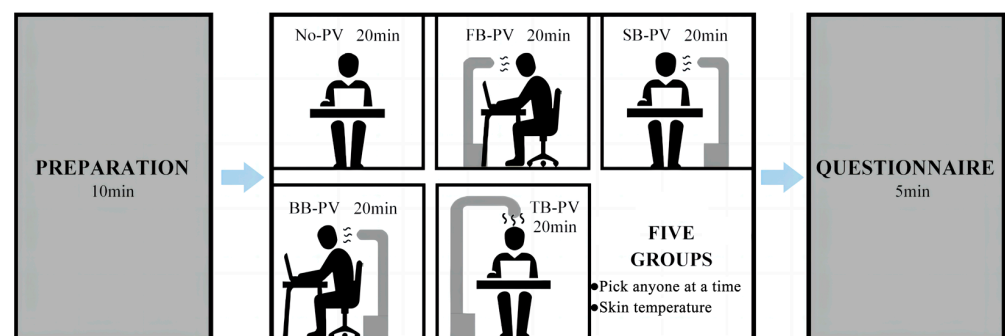


Figure 2. A schematic diagram of the experimental process.

- Before each set of experiments began, the system was turned off. Participants were asked to sit and rest for at least 10 min to avoid interference from other thermal environments or walking, which could affect skin temperature. During this period, the probes of the skin thermometer were installed in the corresponding parts of participants, and they were introduced to the experimental procedures and questionnaires [45].
- Participants selected any experimental group freely and sat for 20 min. Free talk was permitted, but the discussion about the experiment was discouraged. All of them were free to perform computer work or read, with an estimated metabolic rate of 1.0–1.1 met. Their skin temperatures were monitored throughout the entire process [46].
- After 20 min, the system stopped running and participants had 5 min to complete the questionnaire. Then, participants should rest for 10 min to restore the initial state in the controlled temperature–humidity environment. They could enter another group freely to complete the next assessment.
- To avoid the influence of human fatigue on results, all participants only took part in a maximum of two groups per day (approximately 70 min). Each experiment involved a single person and each subject participated in the whole five groups of experiments. The order of the five groups was random.

2.3. Description of Experimental Measurement

In this study, the measured environmental parameters included air temperature, room air speed, relative humidity, and airflow speed around subjects by PV. The skin temperatures were a physiological evaluation parameter, so six body areas, including the cheek, upper arm, chest, lumber, posterior thigh, and anterior thigh, were recorded by the skin thermometers. To ensure optimal contact between the temperature probes of the skin thermometers and the skin's surface, breathable medical tape was utilized to affix the probes, thereby preventing any local discomfort from the attachment process. Mean skin temperature (MST) values were obtained by summing the products of a limited number of local skin temperatures and their corresponding weighting factors. Following evaluation, we chose the following MST calculation formula [47]:

$$\text{MST} = 0.149 T_{\text{CK}} + 0.107 T_{\text{UA}} + 0.186 T_{\text{CT}} + 0.186 T_{\text{LB}} + 0.186 T_{\text{PT}} + 0.186 T_{\text{AT}} \quad (1)$$

where T_{CK} , T_{UA} , T_{CT} , T_{LB} , T_{PT} , and T_{AT} are the local skin temperatures on the cheek, upper arm, chest, lumber, posterior thigh, and anterior thigh, °C.

The measurement interval for all instruments was set at 5 min. And the range of measurement and accuracy utilized in this study are detailed in Table 2.

Table 2. Measuring range and accuracy of the experimental instruments.

Variable	Sensor	Manufacturer and Country	Measuring Range	Accuracy
Air temperature	JT2011	JT Technology Co., Ltd., Beijing, China.	−20~+70 °C	±0.5 °C
Relative humidity			0~95%	±5%
Air speed	JT2023A		0~5 m/s	±(0.03 m/s + 2%)
Skin temperature	iButton DS1923	BOB Technology Co., Ltd., Shanghai, China.	−20~+85 °C	±0.5 °C

2.4. Description of Questionnaire Survey

The recruitment goal was set at 56 subjects, including 28 males and 28 females. The participants were healthy individuals, aged between 20 and 29 years, predominantly working in office environments. They were required to have a history of using cooling devices like fans for more than an average of an hour during summer, which was expected to enable them to provide accurate and objective assessments in the experiment. We conducted preliminary evaluations of potential respondents and if they spent an average of less than an hour using fans in summer, they were not recommended to participate in the experiment. None of the selected participants had prior knowledge of the study's subject matter, and they had been residing locally for several years, indicating acclimatization to the local climate [48]. Meanwhile, they were instructed to refrain from consuming medications or engaging in intense physical activities 24 h prior to the experiment, ensuring they were in optimal physical condition [49]. The attire for all participants was consistent with typical summer clothing, including short T-shirts, short pants or skirts, socks, and shoes or sandals [50]. Calculated based on ASHRAE-2020 [51], the average insulation for all participants was 0.41 ± 0.04 clo (with men's clothing insulation at 0.37 ± 0.01 clo and women's at 0.44 ± 0.02 clo). Detailed information data of subjects are provided in Figure 3.

To investigate the psychological feelings of participants, each individual was mandated to complete a questionnaire during each experimental process. The questionnaire aimed to gauge their perceptions and willingness responses in detail. These questions were designed in accordance with ASHRAE-2020 standards [51]. As detailed in Table 3, the questionnaire encompassed five aspects including thermal sensation vote, airflow sensation vote and its speed preference, thermal comfort vote, and overall willingness vote. The questionnaire also delved into the percentage of discomfort symptoms under varying directions of airflow. All paper questionnaires were collected by researchers after the experimental process. During collection, researchers conducted an initial check to ensure the questionnaires were

completed fully and no critical questions were missed. The questionnaire is depicted in Figure A1.

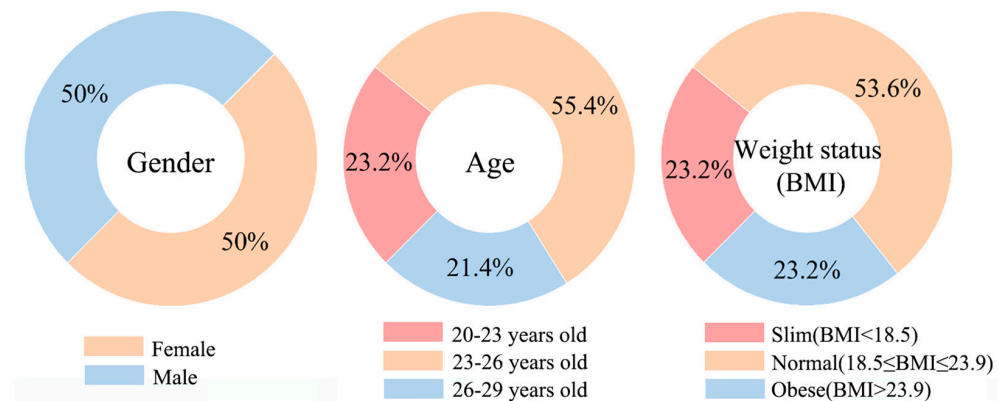


Figure 3. A schematic diagram of subjects' information.

Table 3. Scales of questionnaire parameters.

Scale	Thermal Sensation Vote	Airflow Sensation Vote	Airflow Speed Preference	Thermal Comfort Vote	Overall Willingness Vote
+3	Hot	Very strong	---	Very comfortable	---
+2	Warm	Strong	---	Comfortable	Very willing
+1	Slightly warm	Slightly strong	Turn up	Just comfortable	Willing
0	Neutral	Neutral	No change	Neutral	Neutral
−1	Slightly cool	Slightly weak	Turn down	Just uncomfortable	Unwilling
−2	Cool	Weak	---	Uncomfortable	Very unwilling
−3	Cold	Very weak	---	Very uncomfortable	---

2.5. Description of Statistical Analysis

Data analysis in this study was conducted using IBM SPSS Statistics 27.0.1. To examine potential significant differences in paired quantitative data, such as variations in skin temperature, a paired sample *t*-test was utilized. The determination of statistical significance of the results hinged on the *p*-value. A threshold was set at $p = 0.05$, with results deemed statistically significant if $*p < 0.05$. All experimental data across subjects were presented in the format of mean $\pm$ standard deviation (SD) [46].

3. Results and Discussion

To investigate the impact of airflow direction towards the head in terms of the physiological and psychological feelings of humans, the skin temperature and questionnaire survey were conducted for the 56 participants. The following content provides an analysis and discussion under different experimental conditions.

3.1. Measurement of the Skin Temperatures

The skin temperature is regarded as an extremely important physiological index to evaluate comfort level [52]. Figure 4 depicts the variation in mean skin temperatures across the five groups. As shown, the personalized ventilation could reduce the MST and the airflow direction had a certain difference on reducing the skin temperature. The MST was reduced by approximately 0.5–0.6 °C, 0.4–0.5 °C, 0.4–0.5 °C, and 0.5–0.6 °C for FB-PV,

SB-PV, BB-PV, and TB-PV, respectively, due to the local ventilation. It showed that the consistent airflow towards the head can efficaciously mitigate the mean skin temperature.

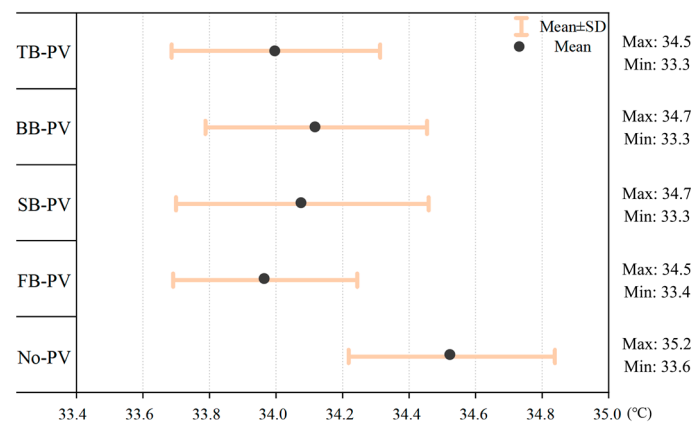


Figure 4. Variation in mean skin temperature across five groups ($p < 0.05$ between No-PV and other groups).

Figure 5 presents the variations in local skin temperature difference in six body parts by taking No-PV as a reference. As displayed, six body parts showed similar variation tendencies. The cheek exhibits the most pronounced temperature difference compared to the other body parts. During FB-PV and TB-PV, the airflow speed near the cheek is relatively high due to being closer to the source. It flows through the skin surface and enhances the heat dissipation efficiency, thereby reducing the skin temperature. They had a higher temperature variation on the cheek and the temperature differences were up to more than 1.5 °C and 1.2 °C, respectively. Moreover, a temperature difference of higher than 0.5 °C was observed in the upper arm, while there were small temperature differences in the four other parts. This phenomenon was due to being further from the airflow source.

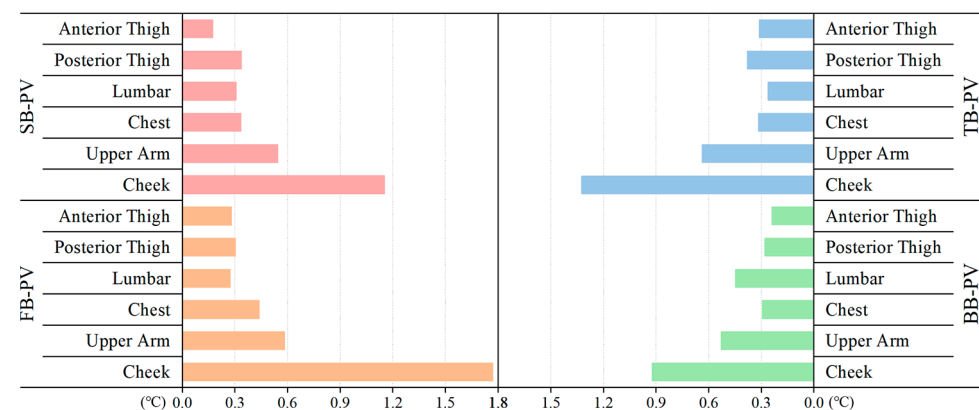


Figure 5. Variation in skin temperature difference in cheek, upper arm, chest, lumbar, posterior thigh, and anterior thigh.

3.2. Voting of Thermal Sensation and Comfort

Figure 6 compared the thermal sensation votes across the five groups. It was clearly seen that the PV system to the head could improve the thermal sensation in the warm and windless environment. After using the system, the votes were reduced to +0.34 (between “Neutral (0)” and “Slightly warm (+1)”), −0.30 (lower than “Neutral (0)”), −0.04 (very close to “Neutral (0)”), and −0.77 (between “Slightly cool (−1)” and “Neutral (0)”) for BB-PV, SB-PV, TB-PV, and FB-PV, respectively. Combined with Figure 4, the parallel variation was found between the skin temperature and thermal sensation vote. Among four experimental

groups, TB-PV, closest to “Neutral (0)”, had the optimal thermal sensation. FB-PV and SB-PV had the cooler sensation.

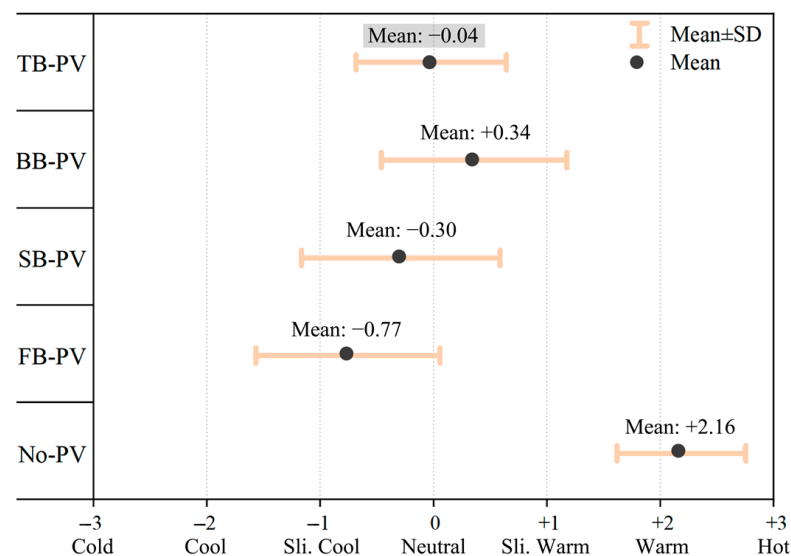


Figure 6. Comparison of thermal sensation votes across five groups ($p < 0.05$ between No-PV and other groups).

Figure 7 delineates the thermal comfort votes from participants. In a 29 °C indoor setting with No-PV, participants predominantly reported discomfort, evidenced by an average score of -2.02 (below “ -2 (Uncomfortable)”). When using PV, there was a discernible improvement in comfort level, yet the mean for the four experimental groups lingered around or below “Just comfortable (+1)”, suggesting only a moderate comfort enhancement. This implies that the rapid and uneven airflow surrounding the local body does not translate into significant comfort. TB-PV exhibited the most uniform airflow around the head and impacted the breathing zone indirectly. It resulted in the highest vote of $+1.05$, marginally above “Just comfortable (+1)”. However, despite FB-PV leading to the greatest reduction in skin temperature and the coolest sensation, it directly impacted on the eyes and breathing zone and culminated in a lowest comfort level of -1.11 (below “Just uncomfortable (-1)”). Therefore, when airflow acts on the head, it is crucial to consider various factors, such as the air temperature and airflow speed, to ensure optimal comfort level.

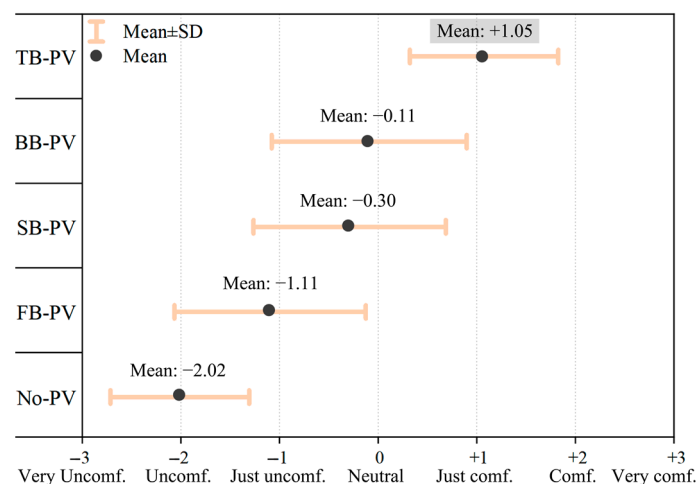


Figure 7. Comparison of thermal comfort votes ($p < 0.05$ between No-PV and other groups).

3.3. Voting of Airflow Sensation, Preference, and Symptom

As shown in Figure 8, the vote for the absence of airflow stood at -2.46 , signifying a distinct sense of weakness. Votes allocated to FB-PV scored $+2.32$ (between “Strong (+2)” and “Very strong (+3)”), indicating the most pronounced perception of airflow. SB-PV and TB-PV garnered votes of $+2.02$ and $+1.88$, respectively. Moreover, the vote for BB-PV amounted to $+1.77$ (below “Strong (+2)”), displaying a moderate strong perception.

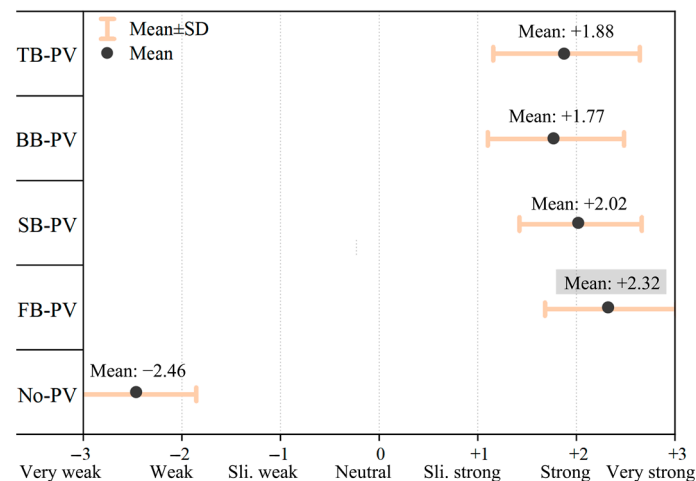


Figure 8. Comparison of airflow sensation vote across five groups ($p < 0.05$ between No-PV and other groups).

In Figure 9, the preference of airflow speed for each direction was depicted, with the percentages reflecting the proportion of votes among all participants. In the context, $+1$ and -1 do not represent specific quantities but rather reflect overall tendencies and choices regarding environmental conditions. In the No-PV setting, all participants consistently voted “Turn up (+1)”, demonstrating that they experienced heat and desired airflow. FB-PV received the majority of “Turn down (-1)” votes. The mean values for FB-PV and SB-PV were recorded at -0.64 and -0.21 , respectively, revealing the higher sensitivity of participants in these conditions. In contrast, the mean of BB-PV was the highest at $+0.43$, exceeding “No change (0)”. Meanwhile, TB-PV stood at -0.04 , closest to the ideal state of “No change (0)”.

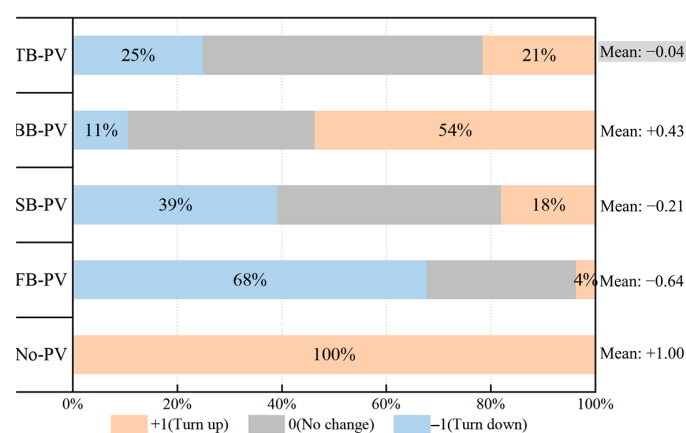


Figure 9. Airflow speed preference under different conditions.

Continuous airflow towards the head introduces a sensation of fresh air [17]. Nonetheless, the airflow towards the breathing zone is particularly concerning, as it may cause symptoms such as dry eyes, myxerxerosis, dizziness, and even headache in partici-

pants [53,54]. Figure 10 illustrates the proportion of discomfort symptoms experienced by participants using the PV system. Notably, FB-PV, which directs airflow towards the eyes and breathing zone, resulted in the highest proportion of related discomfort symptoms. Specifically, instances of dry eyes and mycteroxerosis were reported at 41% and 32%, respectively. With SB-PV, this ratio was 23% and 13%. Conversely, BB-PV and TB-PV, which do not directly affect the breathing zone, demonstrated a lower incidence of discomfort. Thus, when the airflow continues to act on the head, it is imperative to consider not just the cooling effects, but also the potential discomfort caused by excessive airflow towards the breathing zone or uneven airflow across the body, particularly at higher air speeds.

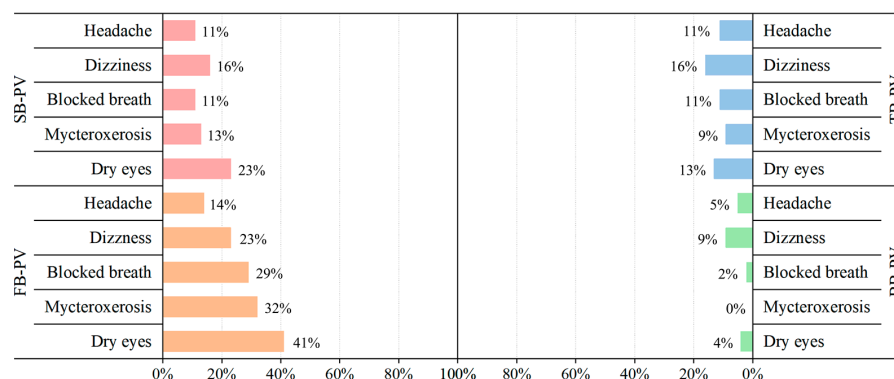


Figure 10. Discomfort symptoms across experimental groups.

3.4. The Correlation Analysis of Airflow Sensation with Thermal Sensation and Comfort

Figure 11 illustrates the distribution of airflow and thermal sensation votes across the five groups. The figures depict individual counts, while the percentages reflect the proportion of these votes in relation to the total counts. In the control group of No-PV, the airflow sensation was almost very weak, with the thermal sensation vote primarily categorized as “Warm (+2)” and “Hot (+3)”. With the usage of PV, participants experienced a notable airflow sensation. Notably, in the FB-PV condition, the vote for airflow sensation was the highest, with around 89% of participants selecting “Strong (+2)” and “Very strong (+3)”. In contrast, the airflow sensation in BB-PV was weaker than the other three experimental groups. FB-PV and SB-PV evoked a cooler sensation among participants, constituting 64% and 39% below “Neutral (0)”, respectively.

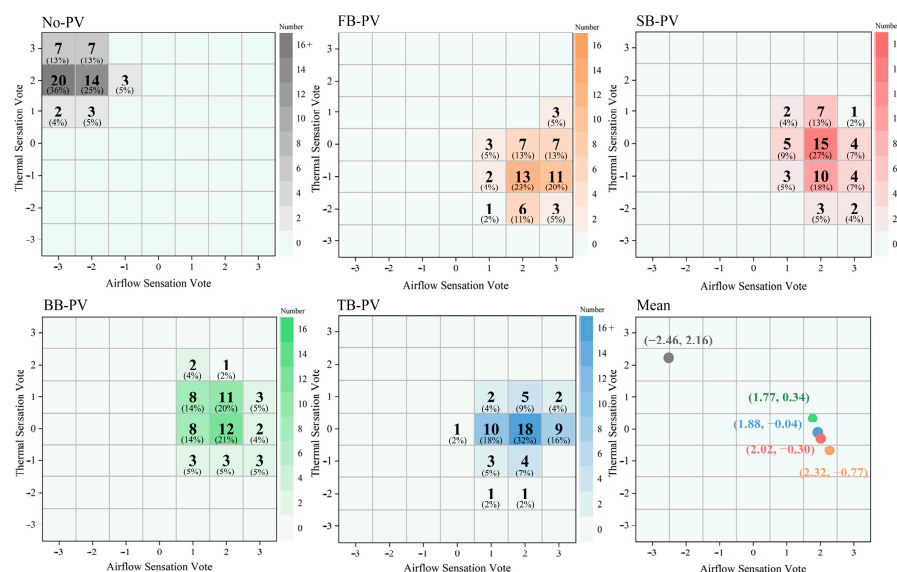


Figure 11. Schematic diagram of airflow sensation with thermal sensation.

Figure 12 depicts the distribution of votes for airflow sensation with thermal comfort among all participants. Votes in the No-PV group were predominantly in the discomfort zone. When using PV towards the head, the airflow sensation is obvious and strong, and the mean vote is between +1.77 and +2.32. Nevertheless, notable discrepancies in thermal comfort arose across various directions. Despite FB-PV inducing the coolest sensation, the airflow affecting the breathing zone caused a perception of discomfort, resulting in the lowest comfort vote. Votes below “Neutral (0)” surpassed 80%. TB-PV demonstrated the highest vote in thermal comfort, with around 80% of votes accumulating in the choices of “Just comfortable (+1)”, “Comfortable (+2)”, and “Very comfortable (+3)”.

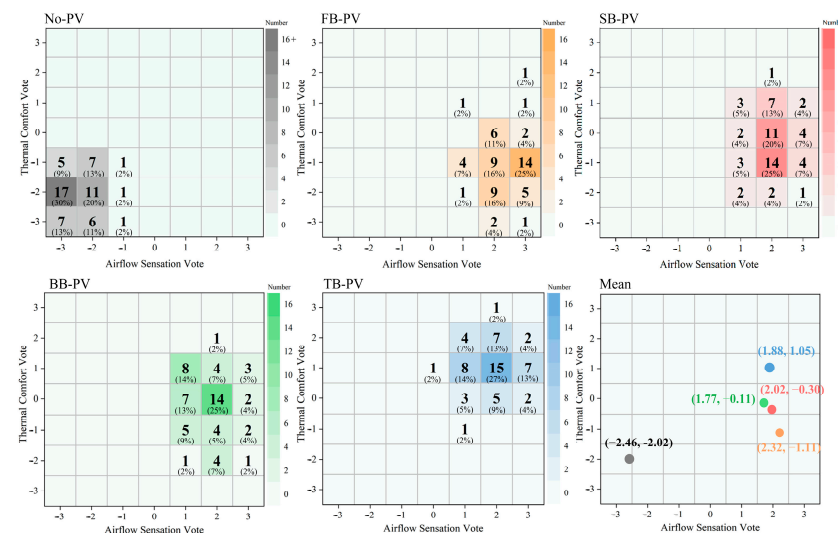


Figure 12. Schematic diagram of airflow sensation with thermal comfort.

3.5. The Overall Willingness Assessment

As illustrated in Figure 13, the overall willingness for varying directions of airflow was evaluated. TB-PV emerged as the most favorable choice, with the score of +1.21 (between “Willing (+1)” and “Very willing (+2)”). It provided a relatively cooling sensation while mitigating the discomfort level with the continuous airflow. FB-PV and SB-PV also garnered relatively high votes, scoring +0.57 and +0.68 (between “Neutral (0)” and “Willing (+1)”), respectively. Despite some participants reporting discomfort with the airflow directly impacting the breathing zone, these conditions were effective in reducing the heat and introducing fresher air directly to the breathing zone. Conversely, BB-PV, not conventionally favored as a cooling direction, recorded the lowest willingness level among participants, with a score of −0.18 (lower than “0 (Neutral)”).

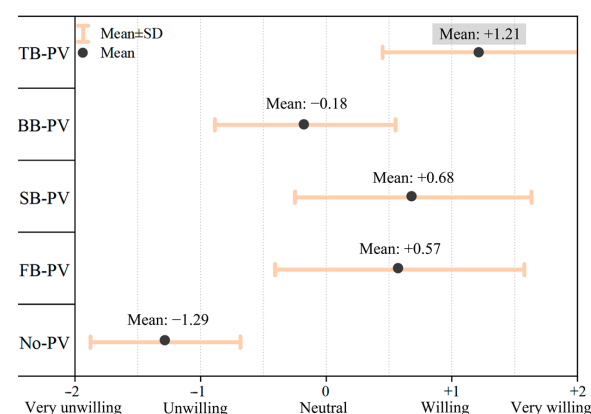


Figure 13. Comparison of overall willingness vote across five groups ($p < 0.05$ between No-PV and other groups).

4. Conclusions

As one of the personalized environmental control technologies, personalized ventilation was employed widely. In order to enhance human comfort, the airflow directions including FB-PV, SB-PV, BB-PV, and TB-PV towards the head and the control group No-PV were assessed in terms of the physiological and psychological feelings of participants. In the No-PV condition, the system is off, while the airflow speed around the head remains at 1.8 m/s for the other four experimental groups. It was conducted under indoor conditions with a designed air temperature of 29.0 ± 0.5 °C and a relative humidity of $60 \pm 5\%$. A total of 56 participants were invited to undergo the thermal environment assessment and the skin temperature measurement. The findings are as follows:

- Skin temperature reduction: FB-PV, SB-PV, BB-PV, and TB-PV towards the head led to MST reductions of 0.4–0.6 °C, which showed that personalized ventilation can efficaciously mitigate the skin temperature.
- Improvement in thermal sensation: personalized ventilation towards the head could improve thermal sensation, especially for FB-PV, whose TSV was -0.77 (between “Slightly cool (-1)” and “Neutral (0)”). TB-PV was -0.04 (very close to “Neutral (0)”), which had the optimal thermal sensation. The same trend was observed for the skin temperature and thermal sensation.
- Enhancement of comfort level: TB-PV demonstrated the highest comfort level with $+1.05$ (slightly higher than “Just comfortable ($+1$)”), while it was on the contrary for FB-PV of -1.11 (slightly lower than “Just uncomfortable (-1)”) due to discomfort in having the freedom to breathe under the continuous airflow.
- Overall willingness evaluation: TB-PV had the highest score of $+1.21$ (between “Willing ($+1$)” and “Very willing ($+2$)”). FB-PV and SB-PV scored $+0.57$ and $+0.68$ (between “Neutral (0)” and “Willing ($+1$)”), respectively. BB-PV was recorded as the lowest level of -0.18 (slightly lower than “ 0 (neutral)”).

We recognize the impact of the airflow direction towards the head on human comfort, which expands the applicability of the PECS in buildings. This investigation aimed to determine which airflow direction optimizes thermal comfort by potentially lowering the mean skin temperature and enhancing subjective comfort ratings. The broader aim was to contribute to the advancement of PECSs, enhancing their ability to meet individual thermal comfort requirements.

This study is subject to certain limitations. For example, perception concerning airflow direction is influenced by other factors, such as air temperature and speed. Furthermore, subjective perceptions may differ among various demographic groups due to factors like gender, age, and activity level within the same spatial context. Subsequent investigations will further explore the comfort levels among different demographic groups and various conditions.

Author Contributions: Conceptualization, W.F.; methodology, C.L.; formal analysis, C.L.; investigation, X.M.; data curation, W.F. and X.M.; writing—original draft preparation, C.L. and W.F.; writing—review and editing, C.L. and X.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

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

Appendix A

QUESTIONNAIRE

BEFORE EXPERIMENT

1. Personal information

Gender: ☐ Male ☐ Female

Age:

Height:

Weight:

2. How much time do you spend on average blowing to cool down in summer?



Less than 1h

☐

1h–4h

☐

4h–7h

☐

7h–10h

☐

More than 10h

☐


DURING EXPERIMENT

3. What is your thermal sensation?



Cold
(-3)

☐

Cool
(-2)

☐

Slightly cool
(-1)

☐

Neutral
(0)

☐

Slightly warm
(+1)

☐

Warm
(+2)

☐

Hot
(+3)

☐


4. What is your airflow sensation?



Too weak
(-3)

☐

Weak
(-2)

☐

Slight weak
(-1)

☐

Neutral
(0)

☐

Slight strong
(+1)

☐

Strong
(+2)

☐

Very Strong
(+3)

☐


5. What is your airflow preference?



Turn down
(-1)

☐

No change
(0)

☐

Turn up
(+1)

☐


6. Which of the symptoms you feel during this situation? (Multiple choices)



Dry eyes

☐

Mycterorosis

☐

Headache

☐

Blocked breath

☐

Dizziness

☐

None

☐


7. How comfortable are you with this situation?



Very
uncomfortable
(-3)

☐

Uncomfortable
(-2)

☐

Just
uncomfortable
(-1)

☐

Neutral
(0)

☐

Just
comfortable
(+1)

☐

Comfortable
(+2)

☐

Very
comfortable
(+3)

☐


8. Are you willing to stay in this environment for a long time?



Very unwilling
(-2)

☐

Unwilling
(-1)

☐

Neutral
(0)

☐

Willing
(+1)

☐

Very willing
(+2)

☐


Figure A1. The questionnaire photo.

References

- Meng, X. Influence of Air-Conditioning Intermittent Operation on the Cooling Load from Opaque Envelopes in Residences. *Case Stud. Therm. Eng.* **2024**, *58*, 104393. [\[CrossRef\]](#)
- Rotas, R.; Fotopoulou, M.; Drosatos, P.; Rakopoulos, D.; Nikolopoulos, N. Adaptive Dynamic Building Envelopes with Solar Power Components: Annual Performance Assessment for Two Pilot Sites. *Energies* **2023**, *16*, 2148. [\[CrossRef\]](#)
- Liu, S.; Ge, W.; Meng, X. Influence of the shading nets on indoor thermal environment and air-conditioning energy consumption in lightweight buildings. *Energy Rep.* **2024**, *11*, 4515–4521. [\[CrossRef\]](#)
- Meng, X. Thermal Performance Assessment of the Dynamic Rotating Latent-Energy-Storage Envelope (DRLESE) during Winter. *Case Stud. Therm. Eng.* **2024**, *60*, 104671. [\[CrossRef\]](#)
- Alsaad, H.; Voelker, C. Performance evaluation of ductless personalized ventilation in comparison with desk fans using numerical simulations. *Indoor Air* **2022**, *30*, 776–789. [\[CrossRef\]](#) [\[PubMed\]](#)
- Alfano, F.R.d.; Olesen, B.W.; Palella, B.I. Povl Ole Fanger's impact ten years later. *Energy Build.* **2017**, *152*, 243–249. [\[CrossRef\]](#)
- Wang, Z.; Dear, R.D.; Luo, M.; Lin, B.; He, Y.; Ghahramani, A.; Zhu, Y. Individual Difference in Thermal Comfort: A Literature Review. *Build. Environ.* **2018**, *138*, 181–193. [\[CrossRef\]](#)
- Ge, L.; Gao, Y.; Meng, X. Employing the spray system to alleviate the thermal action of air-conditioning in summer. *Case Stud. Therm. Eng.* **2024**, *55*, 104133. [\[CrossRef\]](#)
- Yang, B.; Ding, X.; Wang, F.; Li, A. A review of intensified conditioning of personal micro-environments: Moving closer to the human body. *Energy Built Environ.* **2021**, *2*, 260–270. [\[CrossRef\]](#)
- Liu, F.; Yan, L.; Meng, X. A review on indoor green plants employed to improve indoor environment. *J. Build. Eng.* **2022**, *53*, 104542. [\[CrossRef\]](#)
- Makhoul, A.; Ghali, K.; Ghaddar, N. The energy saving potential and the associated thermal comfort of displacement ventilation systems assisted by personalized ventilation. *Indoor Built Environ.* **2013**, *22*, 508–519. [\[CrossRef\]](#)

12. Pan, D.; Chan, M.; Xia, L.; Xu, X.; Deng, S. Performance evaluation of a novel bed-based task/ambient conditioning (TAC) system. *Energy Build.* **2012**, *44*, 54–62. [\[CrossRef\]](#)
13. Godithi, S.B.; Sachdeva, E.; Garg, V.; Brown, R.; Kohler, C.; Rawal, R. A review of advances for thermal and visual comfort controls in personal environmental control (PEC) systems. *Intell. Build Int.* **2019**, *11*, 75–104. [\[CrossRef\]](#)
14. 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. [\[CrossRef\]](#)
15. Shinoda, J.; Bogatu, D.I.; Watanabe, F.; Kaneko, Y.; Olesen, B.W.; Kazanci, O.B. Performance evaluation of a multi-functional personalized environmental control system (PECS) prototype. *Build. Environ.* **2024**, *252*, 111260. [\[CrossRef\]](#)
16. Du, C.; Li, B.; Liu, H.; Wei, Y.; Tan, M. Quantifying the cooling efficiency of air velocity by heat loss from skin surface in warm and hot environments. *Build. Environ.* **2018**, *136*, 146–155. [\[CrossRef\]](#)
17. Cheng, F.; Cheng, Y.; Lin, Z. Experimental study of draft-related local discomfort in a room with stratum ventilation. *Appl. Therm. Eng.* **2023**, *234*, 121259. [\[CrossRef\]](#)
18. Chen, W.; Zhang, H.; Arens, E.; Luo, M.; Wang, Z.; Jin, L.; Liu, J.; Bauman, F.S.; Raftery, P. Ceiling-fan-integrated air conditioning: Airflow and temperature characteristics of a sidewall-supply jet interacting with a ceiling fan. *Build. Environ.* **2020**, *171*, 106660. [\[CrossRef\]](#)
19. Fanger, P.O. Indoor air quality in the 21st century: Search for excellence. *Indoor Air* **2000**, *10*, 68–73. [\[CrossRef\]](#)
20. Melikov, A.K. Personalized ventilation. *Indoor Air Suppl.* **2004**, *14*, 157–167. [\[CrossRef\]](#)
21. Hui, Z.; 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.
22. Wonseok, O.; Kato, S. The effect of airspeed and wind direction on human's thermal conditions and air distribution around the body. *Build. Environ.* **2018**, *141*, 103–116.
23. Melikov, A.K.; Cermak, R.; Majer, M. Personalized ventilation: Evaluation of different air terminal devices. *Energy Build.* **2002**, *34*, 829–836. [\[CrossRef\]](#)
24. Rawal, R.; Schweiker, M.; Kazanci, O.B.; Vardhana, V.; Jin, Q.; Duanmu, L. Personal comfort systems: A review on comfort, energy, and Economics. *Energy Build.* **2020**, *214*, 109858. [\[CrossRef\]](#)
25. Faulkner, D.; Fisk, W.J.; Sullivan, D.P.; Wyon, D.P. Ventilation Efficiencies of Desk-Mounted Task/Ambient Conditioning Systems. *Indoor Air* **1999**, *9*, 273–281. [\[CrossRef\]](#) [\[PubMed\]](#)
26. 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. [\[CrossRef\]](#)
27. Feng, X.; Liao, C.; Cheng, Y. Experimental study on the supply air characteristics and thermal comfort of a novel personalized ventilation air terminal device. *Indoor Built Environ.* **2023**, *32*, 1269–1287. [\[CrossRef\]](#)
28. Zhai, Z.; Metzger, I.D. Insights on critical parameters and conditions for personalized ventilation. *Sustain. Cities Soc.* **2019**, *48*, 101584. [\[CrossRef\]](#)
29. Toftum, J. Air movement—Good or bad. *Indoor Air* **2004**, *14*, 40–45. [\[CrossRef\]](#)
30. Meng, X.; Meng, L.; Gao, Y.; Li, H. A comprehensive review on the spray cooling system employed to improve the summer thermal environment: Application efficiency, impact factors, and performance improvement. *Build. Environ.* **2022**, *217*, 109065. [\[CrossRef\]](#)
31. Zhou, J.; Zhang, X.; Xie, J.; Liu, J. Effects of elevated air speed on thermal comfort in hot-humid climate and the extended summer comfort zone. *Energy Build.* **2023**, *287*, 112953. [\[CrossRef\]](#)
32. Xie, Z.; Xie, Y.; Cao, B.; Zhu, Y. A study of the characteristics of dynamic incoming flow directions of different airflows and their influence on wind comfort. *Build. Environ.* **2023**, *245*, 110861. [\[CrossRef\]](#)
33. Luo, M.; Zhang, H.; Raftery, P.; Zhou, L.; Parkinson, T.; Arens, E.; He, Y.; Present, E. Detailed measured air speed distribution in four commercial buildings with ceiling fans. *Build. Environ.* **2021**, *200*, 107979. [\[CrossRef\]](#)
34. Toftum, J.; Zhou, G.; Melikov, A. Effect of airflow direction on human perception of draught. In Proceedings of the Climate 2000 Conference, Brussels, Belgium, 30 August–2 September 1997.
35. Wang, H.; Ge, B.; Xu, Z.; Li, J.; Zhang, F.; Zhang, G.; Cui, Z. Does packing activity change worker's thermal sensitivity to local cold stimuli compared to sitting state. *Build. Environ.* **2022**, *226*, 109756. [\[CrossRef\]](#)
36. Jia, M.; Choi, J.H.; Liu, H.; Susman, G. Development of facial-skin temperature driven thermal comfort and sensation modeling for a futuristic application. *Build. Environ.* **2022**, *207*, 108479. [\[CrossRef\]](#)
37. Chen, M.; Farahani, A.V.; Kilpeluäinen, S.; Kosonen, R.; Younes, J.; Ghaddar, N.; Ghali, K.; Melikov, A.K. Thermal comfort chamber study of Nordic elderly people with local cooling devices in warm conditions. *Build. Environ.* **2023**, *23*, 110213. [\[CrossRef\]](#)
38. Stevens, J.C.; Marks, L.E.; Simonson, D.C. Regional sensitivity and spatial summation in the warmth sense. *Physiol Behav.* **1974**, *13*, 825–836. [\[CrossRef\]](#)
39. Jin, Q.; Duanmu, L.; Zhang, H.; Li, X.; Xu, H. Thermal sensations of the whole body and head under local cooling and heating conditions during step-changes between workstation and ambient environment. *Build. Environ.* **2011**, *46*, 2342–2350. [\[CrossRef\]](#)
40. Yang, B.; Lei, T.; Yang, P.; Liu, K.; Wang, F. On the Use of Wearable Face and Neck Cooling Fans to Improve Occupant Thermal Comfort in Warm Indoor Environments. *Energies* **2021**, *14*, 8077. [\[CrossRef\]](#)
41. Stevens, J.C.; Choo, K.K. Temperature Sensitivity of the Body Surface over the Life Span. *Somatosens Mot. Res.* **1998**, *15*, 13–28.

42. Cotter, J.D.; Taylor, N.A.S. The Distribution of Cutaneous Sudomotor and Alliesthesial Thermosensitivity in Mildly Heat-Stressed Humans: An Open-Loop Approach. *J. Physiol.* **2005**, *565*, 335–345. [[CrossRef](#)] [[PubMed](#)]
43. Chow, T.T.; Fong, K.F.; Givoni, B.; Lin, Z.; Chan, A.L.S. Thermal sensation of Hong Kong people with increased air speed, temperature and humidity in air-conditioned environment. *Build. Environ.* **2010**, *45*, 2177–2183. [[CrossRef](#)]
44. 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](#)]
45. Hu, C.; Wang, Z.; Bo, R.; Li, C.; Meng, X. Effect of the cooling clothing integrating with phase change material on the thermal comfort of healthcare workers with personal protective equipment during the COVID-19. *Case Stud. Therm. Eng.* **2023**, *42*, 102725. [[CrossRef](#)]
46. Meng, X.; Yan, L.; Liu, F. A new method to improve indoor environment: Combining the living wall with air-conditioning. *Build. Environ.* **2022**, *216*, 108981. [[CrossRef](#)]
47. Liu, W.; Lian, Z.; Deng, Q.; Liu, Y. Evaluation of calculation methods of mean skin temperature for use in thermal comfort study. *Build. Environ.* **2011**, *46*, 478–488. [[CrossRef](#)]
48. Lam, C.K.C.; Cui, S.; Liu, J.; Kong, X.; Ou, C.; Hang, J. Influence of acclimatization and short-term thermal history on outdoor thermal comfort in subtropical South China. *Energy Build.* **2021**, *231*, 110541. [[CrossRef](#)]
49. Ding, N.; Liu, F.; Pang, F.; Su, J.; Yan, L.; Meng, X. Integrating the living wall with the split air conditioner towards indoor heating environment improvement in winter. *Case Stud. Therm. Eng.* **2023**, *47*, 103061. [[CrossRef](#)]
50. Gao, Y.; Meng, L.; Li, C.; Ge, L.; Meng, X. An experimental study of thermal comfort zone extension in the semi-open spray space. *Dev. Built Environ.* **2023**, *15*, 100217. [[CrossRef](#)]
51. ANSI/ASHRAE Standard 55-2020; Thermal Environmental Conditions for Human Occupancy. ASHRAE: Peachtree Corners, GA, USA, 2020.
52. Li, S.; Jia, X.; Cao, B.; Liu, B.; Zhu, Y. Thermal comfort characteristics and heating demand of people with different activity status during extremely cold exposure. *Build. Environ.* **2023**, *228*, 109798. [[CrossRef](#)]
53. Xia, Y.; Niu, J.; Zhao, R.; Burnett, J. Effects of Turbulent Air on Human Thermal Sensations in a Warm Isothermal Environment. *Indoor Air* **2000**, *10*, 289–296. [[CrossRef](#)] [[PubMed](#)]
54. Zhang, H.; Arens, E.; Kim, D.E.; 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](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.