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Gender differences in thermal comfort under coupled environmental factors

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ABSTRACT

This paper aims to explore gender differences in thermal comfort under coupled environmental factors, as previous studies have primarily focused on air temperature alone. The experiment involved 27 subjects, 13 males and 14 females, who experienced 12 different combinations of air temperature and air velocity environmental conditions. The subjective responses and physiological parameters were collected and analyzed. In colder environments, especially when low air temperatures are coupled with elevated air velocity, significant gender differences are observed, as females feel colder, more uncomfortable, and perceive stronger drafts than males. In hotter environments, when high air temperatures are coupled with still air, males tend to feel more uncomfortable and prefer higher air velocity, compared to females. However, few gender differences are observed when high air temperatures are coupled with elevated air velocity. Under colder conditions, forearm temperatures show a stronger correlation with subjective responses, while under hotter conditions, facial skin temperatures demonstrate a stronger correlation, for both genders. Moreover, the Elevated Air Speed Model in ASHRAE 55–2020 is found to overestimates the cooling effect of elevated air velocity for both genders. The findings suggest that gender differences should be properly considered when designing indoor thermal environments, particularly under colder conditions.

1. Introduction

Gender differences are an important aspect of individual differences that are found to have an impact on human thermal comfort. In the 1970 s, Fanger stated that males and females prefer almost the same air temperature [1,2]. Gender differences have been generally considered to be small and insignificant, and Fanger's Predicted Mean Vote (PMV) model did not consider gender and other individual differences [3]. However, as research on thermal comfort has progressed, the influence of gender differences on thermal comfort has been increasingly recognized and emphasized. A review [4] on the topic of gender differences in thermal comfort revealed that an increasing number of studies have found significant differences. The conclusion drawn from the review is that females tend to be more sensitive than males to temperature deviations from the optimal range, and are more likely to express dissatisfaction, particularly in cooler conditions. A review [5] on individual differences found inconsistent results regarding the significance and magnitude of differences in thermal comfort between genders. However, this review noted that many studies suggested that females tend to be more critical of the indoor thermal environments, and more sensitive to deviations from an optimal environment, than males. In recent years, similar findings have been reported from climate chamber studies [6–8] and field studies [9–11]. Moreover, some studies have attempted to explain gender differences in subjective responses by examining the differences in physiological indicators such as core and skin temperature [6,8,12], heart rate variability [13], and basal metabolic rate [7], and showed that males tended to have a stronger thermoregulation ability than females.

In summary, while a number of studies have explored gender differences in thermal comfort, most have focused on the impact of air temperature alone, without fully considering the combined effects of other environmental factors. Environmental factors that can affect human thermal comfort include air temperature, mean radiant temperature, relative humidity, and air velocity. Among these environmental factors, the mean radiant temperature in buildings is often found to be close to the air temperature [14]. According to a study [15] that analyzed over 200,000 field and laboratory measurements, under typical conditions, it is sufficient to measure the air temperature to

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estimate the mean radiant temperature. The relative humidity has been shown to have a limited impact on human thermal comfort when the air temperature is within a comfortable range. However, in hotter environments, the combined effect of temperature and humidity is often considered [16–18]. The air temperature and air velocity are two of the environmental factors that have a significant impact on human thermal comfort and are relatively easy to regulate. In addition to air temperature, air velocity has received increasing attention in recent years. It was shown that elevated air velocity could improve thermal comfort in a hotter environment, while at the same time saving energy [19–23]. The ASHRAE 55–2020 standard [24] proposed the Elevated Air Speed Model to determine the cooling effect and comfort zone at elevated air velocity without occupant control, with an upper limit of 0.8 m/s. Some studies suggested that air velocity could be increased to 1.6 m/s and even higher in hotter environments without causing discomfort [25,26]. Despite the importance of air temperature and air velocity for thermal comfort, there is still a lack of relevant research on gender differences under conditions where these two factors are combined.

This paper aims to investigate gender differences in thermal comfort under coupled air temperature and air velocity conditions, which would insights into gender-specific responses to coupled environmental factors and provide reference for the better design and control of indoor environments. The specific objectives are as follows:

- To investigate the differences of subjective responses in thermal comfort between males and females under the combined impact of air temperature and air velocity.
- To explore which part of the body's skin temperature is more strongly correlated with subjective thermal comfort responses for different genders under the coupled air temperature and air velocity environmental conditions.
- To evaluate the prediction accuracy of the Elevated Air Speed Model in the ASHRAE 55–2020 standard for different genders.

2. Methods

2.1. Experimental conditions

In the design of indoor thermal environments, increasing air velocity is often utilized to improve thermal comfort during summer. However, during winter, high air velocity is generally avoided, as recommended by ASHRAE 55–2020 [24]. Therefore, we primarily focused on summer conditions to investigate the combined effect of air temperature and air velocity on gender differences in thermal comfort. Based on the GB50736-2012 standard [27], which specifies a comfortable air temperature range of 24–28 ℃ for air-conditioned buildings in summer in China, we selected three air temperature levels of 23 ℃, 26 ℃ and 29 ℃ to represent cool, neutral and warm environmental conditions, respectively. We also included an air temperature level of 32 ℃ to represent the free-running condition. According to the ASHRAE 55–2020 [24], the upper limit of air velocity increases with air temperature. Therefore, we designed three levels of air velocity at each air temperature level (23 ℃, 26 ℃, 29 ℃ and 32 ℃), with one level being still air and the other levels increasing as the air temperature increases. The specific parameters of the designed experimental conditions are shown in Table 1.

The air temperature and relative humidity were controlled by the air conditioner and dehumidifier. In this study, the relative humidity was aimed to be controlled within the range of 45–65 % to eliminate its influence. The air velocity was provided by fans and directed towards the face of the participants. The CO_2 concentration was aimed to be controlled below 900 ppm, which meets the requirements of the indoor air quality standard [28].

It should be noted that the sequence of condition cases was randomized in the actual experiment, and the interval between any two experiment cases was more than 24 h. This experiment was conducted in August-September 2022 in an artificial climate chamber at Shanghai Jiao Tong University. The layout of the climate chamber is shown in Fig. 1.

Table 1
Experimental conditions.

Experimental conditions	Air temperature (℃)	Air velocity (m/s)
Case 1	23	≤0.1 (still air)
Case 2	23	0.4
Case 3	23	0.8
Case 4	26	≤0.1 (still air)
Case 5	26	0.8
Case 6	26	1.6
Case 7	29	≤0.1 (still air)
Case 8	29	0.8
Case 9	29	1.6
Case 10	32	≤0.1 (still air)
Case 11	32	1.6
Case 12	32	2.4

2.2. Subjects and experimental procedure

The required sample size of subjects was determined by referring to previous studies on gender differences in thermal comfort, which showed that a sample size of 12 subjects of each gender was sufficient for statistical analysis [6,8,13,29]. A total of 13 males and 14 females, who were healthy students and faculty, were recruited. Their basic information is shown in Table 2.

The subjects were instructed to avoid caffeine, alcohol and high activity before the experiment and to wear typical summer indoor clothing, including short-sleeved t-shirts, trousers, socks and slippers. The clothing insulation is approximately 0.50 clo.

The total duration of the experiment was 1.5 h, with 0.5 h for preparation and 1 h for the formal experiment. The preparation room was maintained at 26 ℃ with still air. Participants were required to arrive in the preparation room 30 min before the formal experiment to put on the equipment and acclimatize to the environment.

Each group consisted of four participants, with an equal gender ratio of 2 males and 2 females. During the formal experiment, participants were asked to complete a subjective questionnaire at 20, 40 and 60 min, and their skin temperatures was continuously recorded at 10-s intervals. The subjects were instructed to remain seated without movement and were allowed to read books and use their mobile phones during the experiment. The metabolic rate of this activity is approximately 1.1 met.

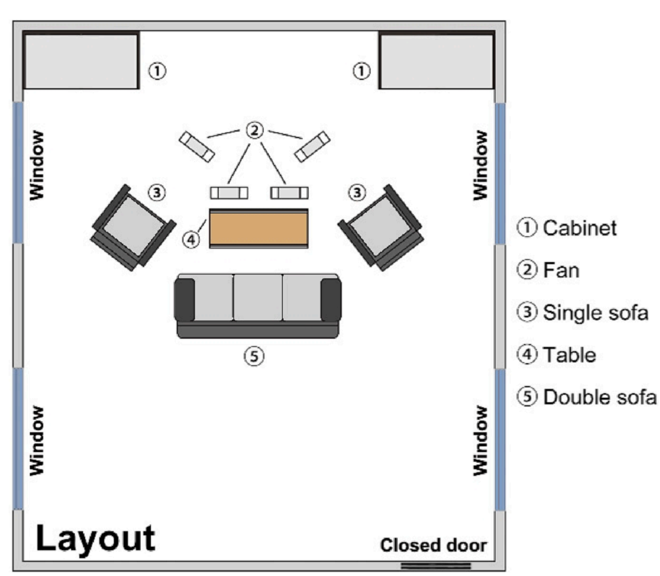

Fig. 1. Layout of the climate chamber.

Table 2
Basic information of subjects.

Gender	Age	BMI	Sample size
Male	23 ± 4.5	22.2 ± 2.4	13
Female	24 ± 5.0	20.1 ± 1.4	14

2.3. Subjective questionnaire and measurement of environmental and physiological parameters

The subjective scales of the questionnaire used in this experiment are shown in Table 3, which refers to the ISO 10551 standard [30]. The questionnaire included subjective assessments of thermal sensation, thermal preference, air velocity preference, draft sensation, thermal comfort, and thermal acceptability.

The instruments and their accuracy for measurement are shown in Table 4. The environmental parameters included air temperature, air velocity, globe temperature and relative humidity. In the actual test, the environmental parameters met the design requirements stated in section 2.1.

The skin temperature was measured at seven points including forehead, cheek, chest, upper arm, forearm, thigh and calf. A previous study has shown that skin temperatures measured on the upper arm, chest, thigh and calf are reliable predictors of human thermal sensation [31]. The skin temperatures were also measured on the forehead and cheek, as air velocity is directed towards the face, and on the forearm, which represents the terminal of the human body.

2.4. Data analysis method

The subjective votes collected at 20, 40 and 60 min were included in the analysis of this experiment, which was based on previous research suggesting that participants typically reach a stable metabolic rate and adapt to a new environment within 20 min [7,32,33].

First, hypothesis test was performed to compare the differences of subjective responses in thermal comfort between males and females. The comparison of gender differences was not performed separately for each environmental condition, but instead, the conditions with common characteristics are combined into the categories, as shown in Table 5.

The air temperature was grouped into two categories (23 °C and 26 °C in one category, 29 °C and 32 °C in another), which categorized the environmental conditions into two types: colder than neutral, and hotter than neutral. This is because that the GB50736-2012 standard [27] considers 26 °C to be a neutral environment, and elevated air velocity can create cooler environment at 23 °C and 26 °C. On the other hand, 29 °C and 32 °C are considered hot environments, and an increase in air velocity would bring the environment closer to neutral.

The subjective scales shown in Table 3 can be categorized into two types: continuous and categorical. The thermal sensation vote is a continuous scale, and the others are considered to be categorical scales. For continuous scale, the *t*-test was used to compare gender differences

Table 3
Subjective scales.

Subjective terms	Wording of degree
Sensation − 3 to 3	Cold, Cool, Slightly cool, Neutral, Slightly warm, Warm, Hot
Thermal preference −1 to 1	Cooler, Not change, Warmer
Air velocity preference −1 to 1	Less, Not change, More
Draft sensation 1 to 4	No sensation, Slightly sensation, Clearly sensation, Strong sensation
Comfort 0 to 4	Comfortable, Slightly uncomfortable, Uncomfortable, Very uncomfortable, Extremely uncomfortable
Acceptability 0 to 1	Acceptable, Not acceptable

Table 4
Instruments for measurement.

Parameters	Instrument	Range	Accuracy
Air temperature	Swema 03+	10–40 °C	±0.2 °C
Air velocity	Swema 03+	0–10 m/s	±0.01 m/s
Globe temperature	Swema 05	0–50 °C	±0.1 °C
Relative humidity	TR-76Ui	10–95 %	±5 %
CO_2	TR-76Ui	0–9999 ppm	±50 ppm
Skin temperature	Pyrobutton	−20–85 °C	±0.2°C

Table 5
Category of environmental conditions.

Environmental characteristics	Air temperature	Air velocity	Environmental conditions
Colder than neutral	Low and neutral	Still	Case 1 (23 °C, ≤0.1 m/s), Case 4 (26 °C, ≤0.1 m/s)
		Elevated	Case 2 (23 °C, 0.4 m/s), Case 3 (23 °C, 0.8 m/s), Case 5 (26 °C, 0.8 m/s), Case 6 (26 °C, 1.6 m/s)
Hotter than neutral	High	Still	Case 7 (29 °C, ≤0.1 m/s), Case 10 (32 °C, ≤0.1 m/s)
		Elevated	Case 8 (29 °C, 0.8 m/s), Case 9 (29 °C, 1.6 m/s), Case 11 (32 °C, 1.6 m/s), Case 12 (32 °C, 2.4 m/s)

in thermal comfort. The level of significance is set as a two-sided *P*-value less than 0.05. In order to improve the reliability of data analysis results, Cohen's effect size (*d*) is performed to access whether difference has scientific and practical significances. For significance analysis in this research, defined values of small, medium and large effect size are 0.2, 0.5 and 0.8 respectively [29,34]. For categorical scales, comparison of gender differences was performed using descriptive statistics based on proportion distribution.

Next, a generalized linear mixed model was performed to investigate the interaction between gender and air velocity at various air temperature level:

$$\mathrm{TSV} = a \cdot V + b \cdot Gender + c \cdot Gender \cdot V + d \tag{1}$$

where TSV is the thermal sensation vote; *V* is the air velocity, m/s; *Gender* is a binary variable including males and females; *a*, *b*, *c* and *d* are parameters estimated by the regression model based on the experiment data.

It should be noted that the main focus in Eq. (1) is on whether the interaction term '$V \cdot Gender$' is significant. This test is performed separately at four different air temperature levels (23 °C, 26 °C, 29 °C and 32 °C). If the interaction term is found to be significant, it suggests that males and females have different subjective perceptions of air velocity at the specified temperature level.

Finally, the Spearman correlation test was used to examine the correlation between skin temperatures at different points on the human body and the subjective responses for males and females.

Data analysis for this study was performed using SPSS version 25.0.

3. Results

3.1. Subjective responses

Fig. 2 and Fig. 3 show the comparison of subjective voting results regarding gender differences in thermal perception, including thermal sensation and thermal preference, respectively.

It can be observed from Fig. 2 that under colder conditions, there is a significant difference in thermal sensation, with female thermal sensation votes significantly lower than male, indicating that they feel colder. Specifically, under still air conditions, the effect size *d* is 0.35, which

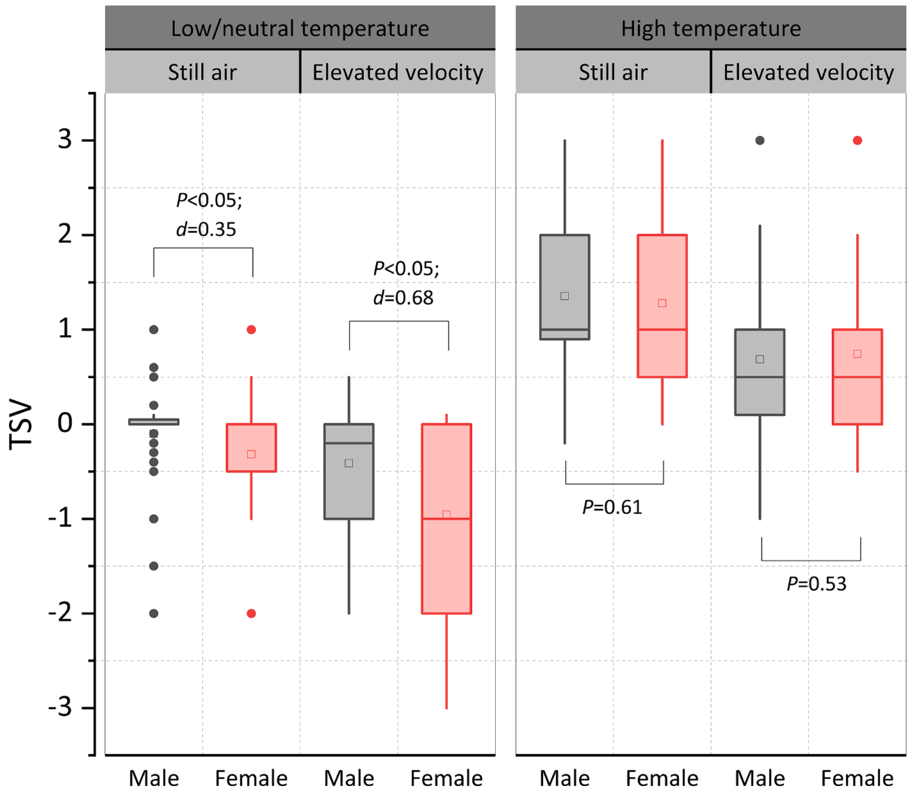

Fig. 2. Comparison of thermal sensation between males and females.

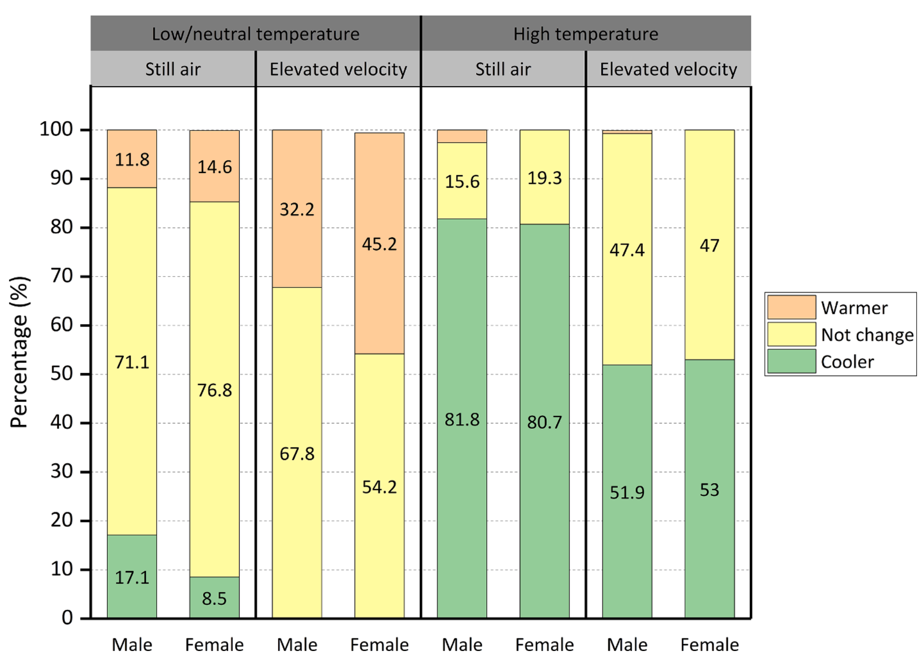

Fig. 3. Comparison of thermal preference between males and females.

does not reach the medium effect of 0.5, while under elevated air velocity conditions, the effect size is 0.68, which exceeds the 0.5 threshold and represents a large difference. This indicates that the combined effect of low/neutral air temperature and elevated air velocity exacerbates gender differences in thermal sensation vote. However, under hotter conditions, no significant difference in thermal sensation is observed under both still and high air velocity conditions. It can be seen that the distribution of thermal preference in Fig. 3 appears to be very similar to the thermal sensation distribution in Fig. 2. Gender differences in thermal preference are mainly observed under colder conditions, particularly in the coupled low/neutral air temperature and elevated air velocity environments, with a higher proportion of females (45.2 %) preferring warmer environments compared to males (32.2 %).

Fig. 4 and Fig. 5 show the comparison of subjective voting results regarding gender differences in air velocity perception, including draft sensation and air velocity preference, respectively.

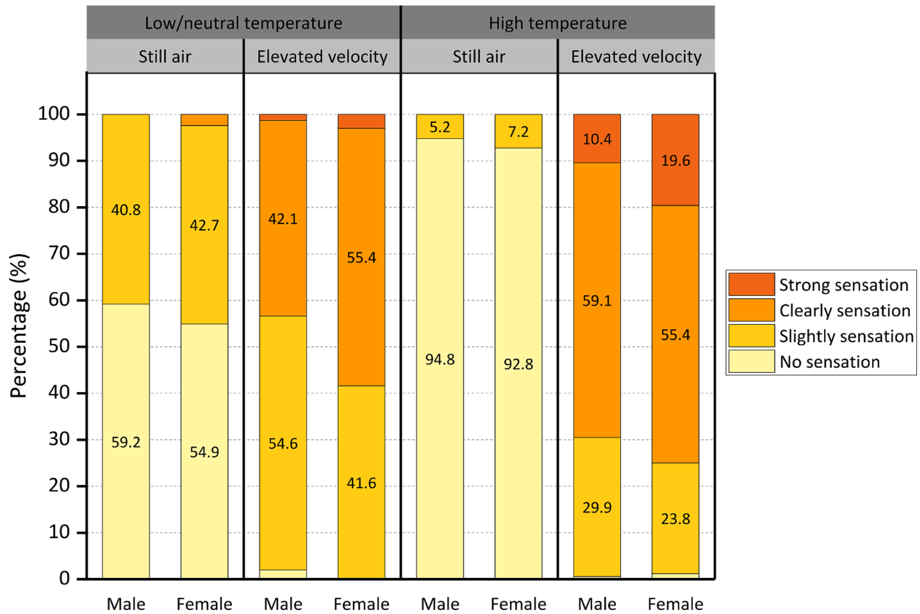

Fig. 4. Comparison of draft sensation between males and females.

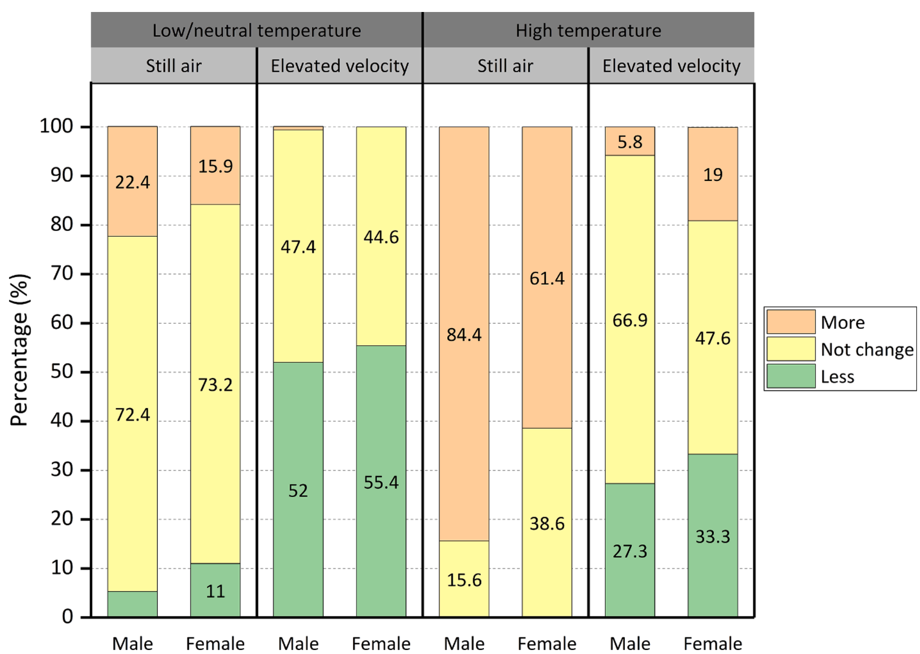

Fig. 5. Comparison of air velocity preference between males and females.

From Fig. 4, it can be seen that females have a stronger perception of air velocity than males under the same conditions, especially in the coupled low/neutral air temperature and elevated air velocity environments, with 58.4 % of females feel a clearly or strong draft sensation, while only 43.4 % of males feel the same. From Fig. 5, it can be seen that a higher proportion of females prefer the air velocity not change or less, compared to males. Notably, under the condition of coupled high air temperature and still air, a significant higher proportion of males (84.4%) preferring more air velocity compared to females (61.4%).

Fig. 6 and Fig. 7 show the comparison of subjective voting results regarding gender differences in overall thermal environment perception, including comfort and acceptability, respectively.

From Fig. 6, it can be observed that when low/neutral air temperature and elevated air velocity are coupled, the proportion of females reporting uncomfortable is 18.6%, significantly higher than the 4.0% of males. This is consistent with the result in Fig. 2, indicating that females feel colder in the cooler environment. When the high air temperature is coupled with still air, the proportion of males reporting uncomfortable is 40.3%, higher than females at 21.7%. This is consistent with the result in Fig. 5, which indicates that males prefer higher air velocity in the condition of coupled high air temperature and still air. The distribution of thermal acceptability in Fig. 7 is very similar to that in Fig. 6, if the comfortable and slight uncomfortable are considered as acceptable, and uncomfortable, very uncomfortable and extremely uncomfortable are considered as not acceptable. This is because the thermal comfort voting and thermal acceptability voting are both considered to be the overall perception of the thermal environment, with similar characteristics.

Fig. 8. shows the interaction between gender and air velocity at

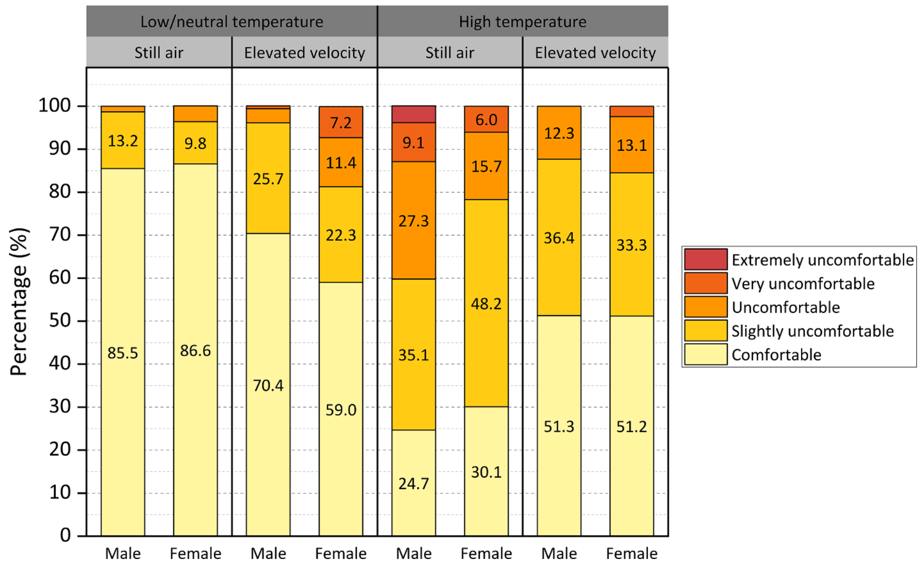

Fig. 6. Comparison of thermal comfort vote between males and females.

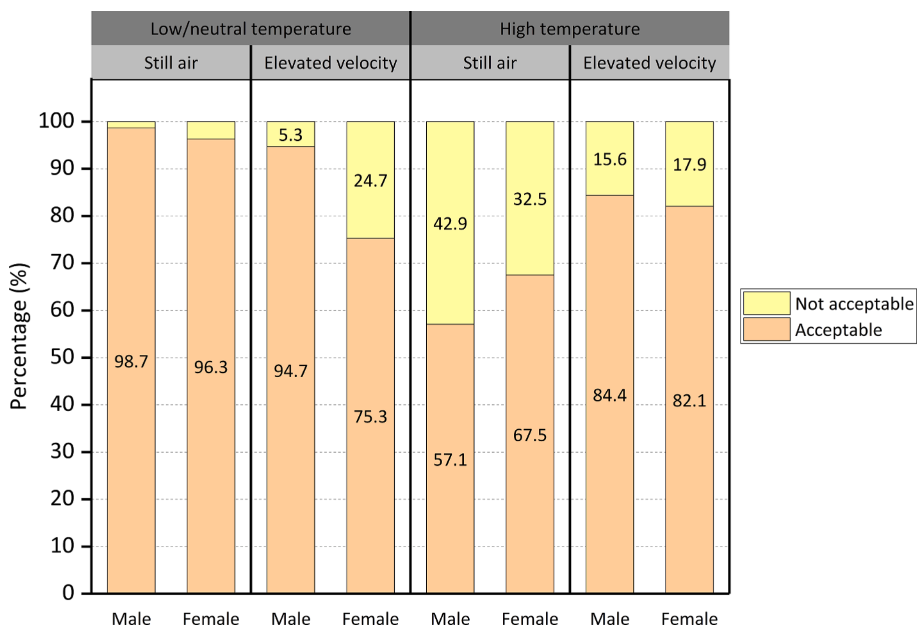

Fig. 7. Comparison of thermal acceptability between males and females.

different air temperature levels.

The interaction term '*Gender* ·*V*' is significant at air temperatures of 23 ℃ and 26 ℃, suggesting that female's thermal sensation decreases more with increasing air velocity compared to males. However, at air temperatures of 29 ℃ and 32 ℃, the interaction term '*V* · *Gender*' is not found to be significant. This indicates that increasing air velocity tends to have a similar cooling effect on both genders under hot conditions.

3.2. Skin temperature

Fig. 9 shows the correlation matrix between the skin temperatures at different body part and subjective responses of males and females under colder conditions.

Due to the orientation of the subjective voting scale, some correlation coefficients, such as thermal sensation, are positive, indicating that the higher the skin temperature under cooler conditions, the higher the thermal sensation. And some are negative, such as thermal comfort, indicating that in cooler conditions, the higher the skin temperature, the more comfortable the human body feels, which is reflected in the decrease in the values of the thermal comfort vote. The darker the color, the higher the correlation coefficient, and the correlation coefficient values of the skin temperature that are most highly correlated with each subjective indicator are marked out. It can be observed that in the colder environments, coupled with air temperature and velocity, the correlation coefficient between the forearm skin temperatures and most of the subjective responses is the highest for both males and females. This may be because the forearm is located at the end of the human body and is exposed to the environment, making it more sensitive to environmental changes, especially in colder environments [35]. The only exception is the correlation between the skin temperature of the forehead and cheek and the draft sensation, which is higher due to the direct airflow on the facial area.

Fig. 10 shows the comparison of forearm skin temperatures between males and females.

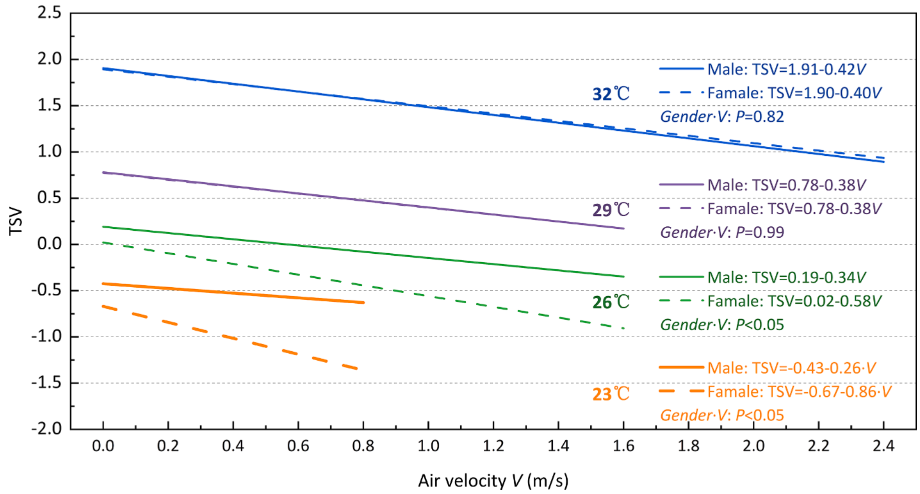

Fig. 8. Interaction between gender and air velocity at different air temperature levels.

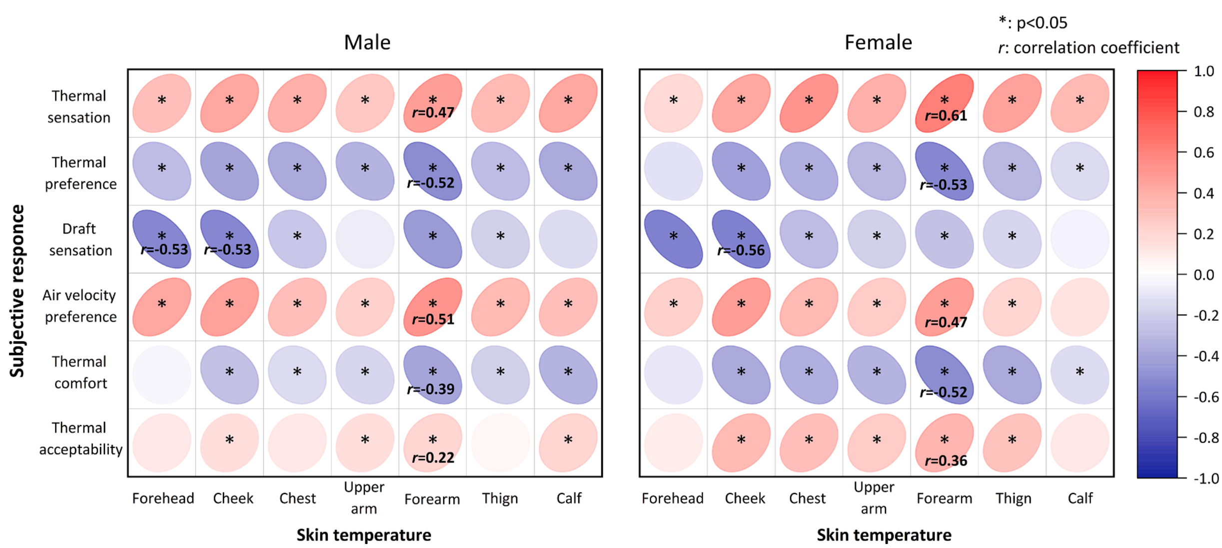

Fig. 9. Correlation between subjective responses and skin temperatures under cooler conditions.

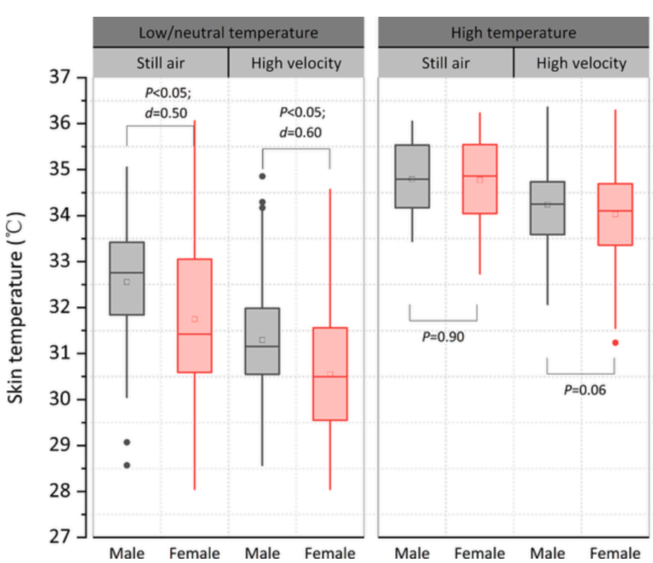

Fig. 10. Comparison of forearm skin temperatures between males and females.

It can be observed that under colder conditions, females have significantly lower forearm skin temperatures than males, while under hotter conditions, there is no significant difference in skin temperatures between genders, which are consist to the subjective thermal sensation shown in Fig. 2. This may be because males have been shown to have stronger thermoregulatory abilities than females, which ensures peripheral skin temperature through increased metabolic rate and blood regulation under colder conditions, which can maintain the skin temperature at the end of the human body.

Fig. 11 shows the correlation matrix between the skin temperatures at different body part and subjective responses of males and females under hotter conditions.

Under the hot conditions, however, the correlation between forehead and cheek skin temperature and subjective responses is higher for both males and females. This may be because in a hotter environment, the skin temperature on the face is more uniform [36]. This is different from a colder environment, where skin temperature is not evenly distributed across the face [37–39], which may result in a lower correlation between single-point facial skin temperature and subjective responses. As it is environmental conditions coupled with air temperature and air velocity, and the air velocity directly towards the face, the skin temperature on the face is expected to have a strong correlation with the subjective

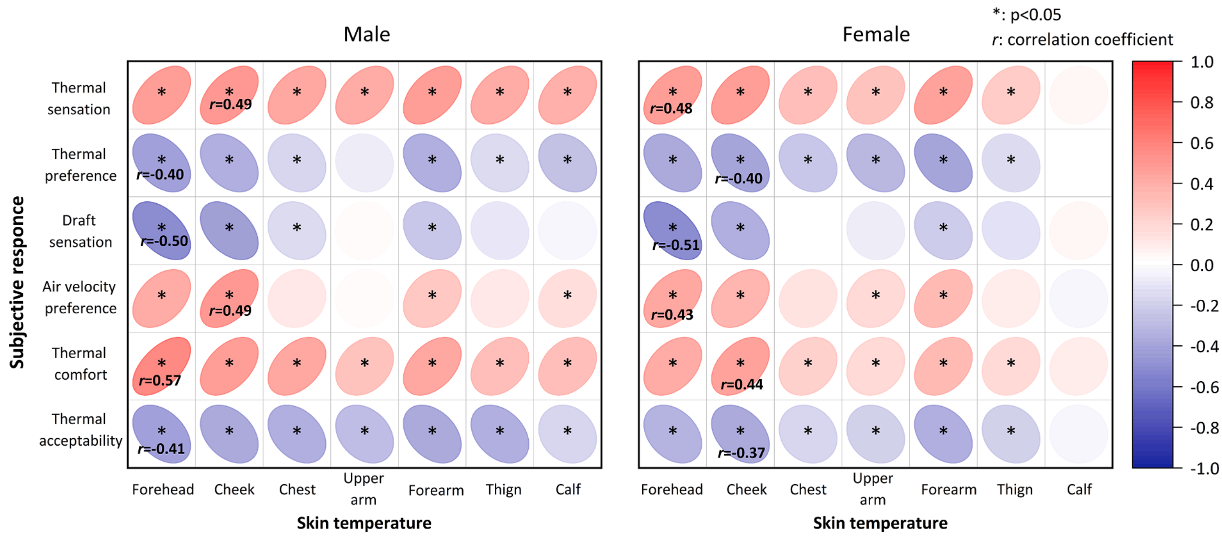

Fig. 11. Correlation between subjective responses and skin temperatures under hotter conditions.

responses of human subjects.

4. Discussion

4.1. Evaluation the prediction performance of elevated air Speed model in ASHRAE 55–2020

In the ASHRAE 55–2020 standard, the evaluation of thermal comfort is based on the PMV model, and the existing version considers the correction for elevated air velocity. For high air velocity conditions, a cooling effect model based on the standard effective temperature (SET) is recommended. In this study, these two models are examined separately.

Fig. 12 shows the prediction performance of the PMV model based on the data obtained in this experiment.

The blue line represents the PMV model's prediction, while the black and red lines are the regression based on actual data for males and females, respectively. It can be seen that under colder conditions, the PMV model overestimates cold discomfort, while under hotter conditions it overestimates hot discomfort, indicating that the human comfort range is wider than the range predicted by the PMV model. It can also be observed that females are more sensitive than males to environments changes, as reflected by the steeper slope of the red line compared to the black line. These findings are consistent with many previous studies [4,5,40,41].

Fig. 13 shows the prediction performance of the cooling effect model based on the SET in ASHRAE55-2020 standard.

The blue line represents the model predicted value, which means the cooling effect of elevated air velocity on subjective responses at a certain air temperature, equivalent to how much temperature reduction. The green line is the mean measured value for both genders, the black line is for males, and the red line is for females. It can be seen that the model overestimates the cooling effect of elevated air velocity, for example, the model suggests that at 29 ℃, increasing air velocity from still air to 0.8 m/s is equivalent to a temperature reduction of 3 ℃. However, the measured value is equivalent to a temperature reduction of only about 1.2 ℃. This finding is similar to the previous results [21,22,26]. Developing a more accurate thermal comfort prediction model that considers the combined effects of environmental parameters and individual differences may be necessary.

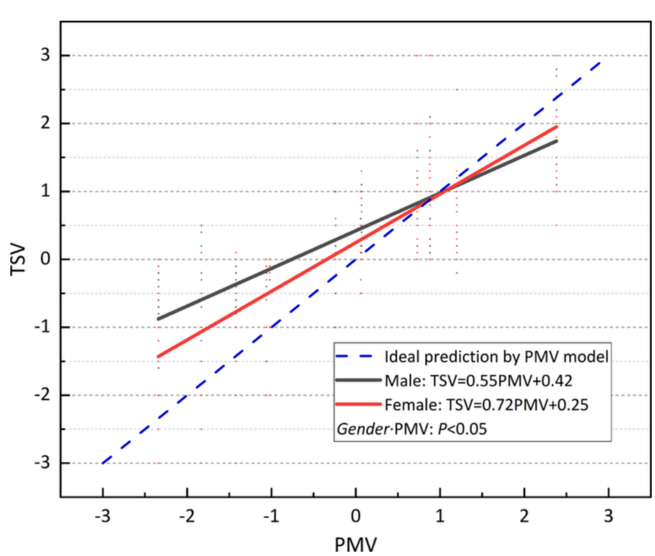

Fig. 12. Evaluation the prediction performance of the PMV model in ASHRAE 55–2020.

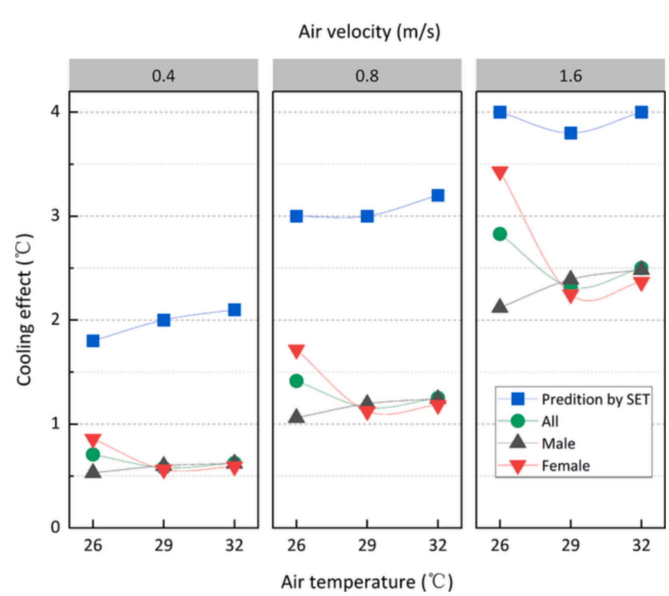

Fig. 13. Evaluation the prediction of cooling effect model in ASHRAE 55–2020.

4.2. Limitations and future work

In this study, the subjective responses and skin temperature were investigated for different genders under coupled air temperature and air velocity conditions. Skin temperature was measured at seven points, including the forehead, cheek, chest, upper arm, forearm, thigh, and calf. It was found that under colder conditions, the forearm skin temperature had the highest correlation with subjective responses, while under hotter conditions, the facial skin temperature had the highest correlation with subjective responses. However, the skin temperature measurements were based on contact methods, and temperature points such as the nose tip and eyes could not be measured, and skin temperature uniformity could not be calculated. Therefore, if skin temperature can be measured using infrared thermography and computer vision, it may be possible to find better skin temperature indicators to characterize gender differences in thermal comfort, and it may also help to establish more accurate thermal comfort prediction models for different individuals. Furthermore, core temperature and breath temperature may also serve as potential physiological indicators [42]. These issues are beyond the scope of this paper, but will be addressed in future studies.

In this study, we controlled other individual factors unchanged, such as young adults, normal BMI, and sedentary status, to investigate gender differences in thermal comfort. Therefore, the conclusions regarding gender differences in thermal comfort may only be applicable under such conditions. We will consider introducing these factors for more in-depth research in the future. Furthermore, this study was conducted in a climate chamber, and these conclusions will be further validated in uncontrolled environments in the future.

5. Conclusions

This paper explores gender differences in thermal comfort under coupled air temperature and air velocity conditions, based on subjective responses and objective physiological parameters. The findings suggest that gender differences in thermal comfort are not straightforward and may depend on the interaction effects of multiple thermal environmental factors. The results are summarized as follows:

1. In a colder environment, especially under coupled low air temperature and elevated air velocity condition, there are significant gender differences in thermal comfort. Females feel colder, more discomfort, and perceive stronger draft, compared to males.
2. In a hotter environment, when high air temperature is coupled with still air velocity, males tend to feel more discomfort and prefer higher air velocity, compared to females. When high air temperature is coupled with elevated air velocity, however, there are few gender differences in thermal comfort.
3. Under coupled air temperature and air velocity conditions, the correlation between forearm skin temperatures and subjective responses is stronger in colder environments, while the correlation between facial skin temperatures and subjective responses is stronger in hotter environments, for both males and females.
4. Existing thermal comfort models often overestimate the impact of environmental factors on the subjective responses and do not account for gender differences, which can lead to errors in practical application. It is recommended that gender differences should be properly considered in the design of thermal environments, especially to avoid the combination of low air temperature and high air velocity that can cause discomfort for females.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

[1] P.O. Fanger, Assessment of man's thermal comfort in practice, Br. J. Ind. Med. 30 (4) (1973) 313–324.
[2] P.O. Fanger, J. Hojbjerre, J. Thomsen, Thermal Comfort Conditions in the Morning and in the Evening, Int. J. Biometeorol. 18 (1) (1974) 16–22.
[3] P.O. Fanger, Thermal comfort, Analysis and Applications in Environmental Engineering, Danish Technical Press, Copenhagen, 1970.
[4] S. Karjalainen, Thermal comfort and gender: a literature review, Indoor Air 22 (2) (2012) 96–109.
[5] Z. Wang, R. de Dear, M. Luo, B. Lin, Y. He, A. Ghahramani, Y. Zhu, Individual difference in thermal comfort: A literature review, Build. Environ. 138 (2018) 181–193.
[6] J. Xiong, Z. Lian, X. Zhou, J. You, Y. Lin, Investigation of gender difference in human response to temperature step changes, Physiol Behav 151 (2015) 426–440.
[7] L. Yang, S. Zhao, S. Gao, H. Zhang, E. Arens, Y. Zhai, Gender differences in metabolic rates and thermal comfort in sedentary young males and females at various temperatures, Energ. Buildings 251 (2021) 111360.
[8] Q. Zhao, J. Lyu, H. Du, Z. Lian, Z. Zhao, Gender differences in thermal sensation and skin temperature sensitivity under local cooling, J Therm Biol 111 (2023), 103401.
[9] S. Lu, B. Pang, Y. Qi, K. Fang, Field study of thermal comfort in non-air-conditioned buildings in a tropical island climate, Appl Ergon 66 (2018) 89–97.
[10] F. Zhang, R. de Dear, Impacts of demographic, contextual and interaction effects on thermal sensation—evidence from a global database, Build. Environ. 162 (2019) 106286.
[11] T. Parkinson, S. Schiavon, R. de Dear, G. Brager, Overcooling of offices reveals gender inequity in thermal comfort, Sci Rep 11 (1) (2021) 23684.
[12] H. Kim, C. Richardson, J. Roberts, L. Gren, J.L. Lyon, Cold hands, warm heart, Lancet 351 (9114) (1998) 1492.
[13] L. Lan, Z. Lian, W. Liu, Y. Liu, Investigation of gender difference in thermal comfort for Chinese people, Eur J Appl Physiol 102 (4) (2008) 471–480.
[14] H. Du, Z. Lian, D. Lai, L. Duanmu, Y. Zhai, B. Cao, Y. Zhang, X. Zhou, Z. Wang, X. Zhang, Z. Hou, Comparison of thermal comfort between radiant and convective systems using field test data from the Chinese Thermal Comfort Database, Build. Environ. 209 (2022) 108685.
[15] M. Dawe, P. Raftery, J. Woolley, S. Schiavon, F. Bauman, Comparison of mean radiant and air temperatures in mechanically-conditioned commercial buildings from over 200,000 field and laboratory measurements, Energ. Buildings 206 (2020) 109582.
[16] S.L. Jing, B.Z. Li, M.L. Tan, H. Liu, Impact of relative humidity on thermal comfort in a warm environment, Indoor Built Environ 22 (4) (2013) 598–607.
[17] B. Li, C. Du, M. Tan, H. Liu, E. Essah, R. Yao, A modified method of evaluating the impact of air humidity on human acceptable air temperatures in hot-humid environments, Energ. Buildings 158 (2018) 393–405.
[18] D. Kong, H. Liu, Y. Wu, B. Li, S. Wei, M. Yuan, Effects of indoor humidity on building occupants' thermal comfort and evidence in terms of climate adaptation, Build. Environ. 155 (2019) 298–307.
[19] Y. Zhai, H. Zhang, Y. Zhang, W. Pasut, E. Arens, Q. Meng, Comfort under personally controlled air movement in warm and humid environments, Build. Environ. 65 (2013) 109–117.
[20] Y. He, W. Chen, Z. Wang, H. Zhang, Review of fan-use rates in field studies and their effects on thermal comfort, energy conservation, and human productivity, Energ. Buildings 194 (2019) 140–162.
[21] S. Zhang, F. Cheng, X. Zhang, Z. Lin, Y. Cheng, Cooling effect of air movement of advanced air distribution under heating mode: Experimental analyses of stratum ventilation, Build. Environ. 231 (2023).
[22] J. Zhou, X. Zhang, J. Xie, J. Liu, Effects of elevated air speed on thermal comfort in hot-humid climate and the extended summer comfort zone, Energ. Buildings 287 (2023) 112953.
[23] J. Zhou, X. Zhang, J. Xie, J. Liu, Occupant's preferred indoor air speed in hot-humid climate and its influence on thermal comfort, Build. Environ. 229 (2023) 109933.
[24] ANSI, ASHRAE, ANSI, ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and AirConditioning Engineers, Atlanta, GA, USA, 2020.
[25] T.T. Chow, K.F. Fong, B. Givoni, Z. Lin, A.L.S. Chan, Thermal sensation of Hong Kong people with increased air speed, temperature and humidity in air-conditioned environment, Build. Environ. 45 (10) (2010) 2177–2183.
[26] Y. Zhai, Y. Zhang, H. Zhang, W. Pasut, E. Arens, Q. Meng, Human comfort and perceived air quality in warm and humid environments with ceiling fans, Build. Environ. 90 (2015) 178–185.

[27] Ministry of Housing Urban and Rural Development, Design Code for Heating, Ventilation and Air Conditioning in Civil Buildings (GB 50736–2012), China Architecture & Building Press, Beijing, China, 2012. In Chinese.
[28] State Administration for Market Regulation and Standardization Admin-istration, Indoor Air Quality Standard (GB 18883–2022), Standars Press of China, Beijing, China, 2022. In Chinese.
[29] L. Lan, Z. Lian, Application of statistical power analysis – How to determine the right sample size in human health, comfort and productivity research, Build. Environ. 45 (5) (2010) 1202–1213.
[30] ISO. ISO 10551: Ergonomics of the Thermal Environment—Assessment of the Influence of the Thermal Environment using Subjective Judgement Scales. Geneva: International Organization for Standardization, 2019.
[31] W. Liu, Z. Lian, Q. Deng, Y. Liu, Evaluation of calculation methods of mean skin temperature for use in thermal comfort study, Build. Environ. 46 (2) (2011) 478–488.
[32] C.P. Chen, R.L. Hwang, S.Y. Chang, Y.T. Lu, Effects of temperature steps on human skin physiology and thermal sensation response, Build. Environ. 46 (11) (2011) 2387–2397.
[33] W. Ji, M. Luo, B. Cao, Y. Zhu, Y. Geng, B. Lin, A new method to study human metabolic rate changes and thermal comfort in physical exercise by CO2 measurement in an airtight chamber, Energ. Buildings 177 (2018) 402–412.
[34] J. Cohen, Statistical power analysis for the behavioural sciences, 2nd ed., Hillsdale, New Jersey, 1988.
[35] Y. Deng, B. Cao, B. Liu, Y. Zhu, Effects of local heating on thermal comfort of standing people in extremely cold environments, Build. Environ. 185 (2020) 107256.
[36] X. Tian, R. Xu, W. Liu, Facial skin temperature and overall thermal sensation of sub-tropically acclimated Chinese subjects in summer, J Therm Biol 112 (2023), 103422.
[37] Y. Wu, B. Cao, Recognition and prediction of individual thermal comfort requirement based on local skin temperature, Journal of Building Engineering 49 (2022) 104025.
[38] Y. He, H. Zhang, E. Arens, A. Merritt, C. Huizenga, R. Levinson, A. Wang, A. Ghahramani, A. Alvarez-Suarez, Smart detection of indoor occupant thermal state via infrared thermography, computer vision, and machine learning, Build. Environ. 228 (2023) 109811.
[39] X. Tian, J. Yu, W. Liu, Facial skin temperature and its relationship with overall thermal sensation during winter in Changsha, China, Indoor Air 32 (10) (2022) e13138.
[40] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE global thermal comfort database II, Build. Environ. 153 (2019) 205–217.
[41] H. Du, Z. Lian, D. Lai, L. Duanmu, Y. Zhai, B. Cao, Y. Zhang, X. Zhou, Z. Wang, X. Zhang, Z. Hou, Evaluation of the accuracy of PMV and its several revised models using the Chinese thermal comfort Database, Energ. Buildings 271 (2022) 112334.
[42] X. Xu, Y. Yang, T. Cao, T. Nie, Z. Lian, Four kinds of body temperatures and their relationships with thermal perception, J. Therm. Biol. (2023) 103600.