Investigation of the effects of face masks on thermal comfort in Guangzhou, China

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ABSTRACT

Wearing masks to study and work places has become a daily protective measure during the COVID-19 pandemic. In the summer of 2021, environmental parameters were monitored, and students in a university library in Guangzhou, China, were surveyed to analyze the possible symptoms of wearing masks for a long time, and to assess the sensitivity of various body parts to the environmental parameters. Concurrently, the preference of subjects wearing masks for various environmental parameters was also analyzed. Additionally, the relationship between thermal sensation and thermal index was analyzed to identify acceptable and comfortable temperature ranges. The expected duration of wearing masks was counted. Subjects wearing masks had greater requirements for environmental comfort, and reported increased thermal discomfort of the face and head, compared to those without masks. More than 70% of the subjects wearing masks reported that they experienced discomfort on their faces. Among the subjects who experienced discomfort, 62.7% reported that facial fever was the main symptom; while some reported symptoms of dyspnea (25.4%) and rapid heartbeat (9.1%). More than 75% of the subjects were expected to wear masks for 2.0 h or less. Evaluation of environmental thermal sensation, including overall, facial, and head thermal sensation, differed among subjects who wore and did not wear masks. The indexes of neutral Operative temperature/Standard Effective Temperature (T_{op}/SET^*) and preferred T_{op}/SET^* were lower among subjects with masks than among those without masks. The neutral T_{op}/SET^* deviation was 0.3 °C, and the preferred T_{op}/SET^* deviation was 0.5 °C. Additionally, the acceptable and comfortable temperature zones differed between the two cases. The subjects who wore masks preferred colder temperatures. These findings indicated that the environmental parameters should be adjusted to improve the thermal comfort of the human body while wearing masks in work or study places.

1. Introduction

On March 11, 2020, the World Health Organization (WHO) declared the COVID-19 outbreak as a pandemic [1]. The emergence and rapid spread of COVID-19, caused by SARS-CoV-2, has led to approximately 180 million confirmed cases and nearly 4 million deaths worldwide as of June 19, 2021 [2]. It had an unprecedented impact globally, leading to a 2%–3% increase in the global mortality rate [3]. SARS-CoV-2 spreads through direct contact when a symptomatic person coughs, sneezes, speaks, or exhales [4–6]. The main symptoms of COVID-19 are fever, fatigue, and dry cough, accompanied by nasal congestion, runny nose, and diarrhea in some patients [7]. The main measures for preventing infection are sanitization, vaccination, and wearing masks [8–10]. Masks have become essential commodities in the daily lives of people during traveling, working, and studying. Wearing masks in public places is the most effective and economical method to prevent

human-to-human transmission of the virus and regulate the COVID-19 outbreak [11]. Such a widespread use of masks, thus, necessitates the need to comprehensively investigate the impact of masks on human thermal comfort.

1.1. Literature review

Personal medical masks typically consist of three layers with a melt-blown microfiber filter between two layers of spunbond fabric. The melt-blown layer acts as the main filter, preventing microorganisms from entering or leaving the mask. The outer non-woven fabric has the properties of liquid resistance and rejection of external droplets, and the inner non-woven fabric has the properties of skin affinity and moisture absorption [12,13]. In manikin studies, medical masks were highly effective for both source control and primary prevention under tidal breathing and coughing conditions [14,15]. Despite their acknowledged benefits for protection and insulation against toxins and viruses, using masks causes side effects as they induce a microclimate of high temperatures and thick humid air; additionally, wearing masks can lead to significant discomfort and breathing difficulties for most people [14]. Further, the air temperature in the mask has a significant impact on human thermal sensation [16].

Previous studies on indoor thermal comfort [17–27] without masks have been conducted. Gabriel et al. [22] found that the neutral temperatures from TSV in Quito, Guayaquil, and Tena in Ecuador were 21.8 °C, 26.3 °C, and 26.9 °C respectively. Wang et al. [23] found that at different temperatures students' performance could be affected, depending on the task being performed. Fang et al. (2018) reported an 80% comfortable temperature range of 21.6–26.8 °C with a mean insulation value of 0.42 clo in Hong Kong [24], and Dhaka et al. (2017) reported an 80% acceptable *SET** range of 23.4–26.6 °C with a mean insulation value of 0.55 clo in India [25]. These studies were conducted prior to the pandemic and hence, did not factor the effect of masks; however, since the pandemic was declared, wearing masks in public places has become mandatory to wear masks to prevent the COVID-19 infection [28–32]. Therefore, further research is needed on human thermal comfort in public places where wearing masks is an essential requirement.

1.2. Research objective

In this investigation, the subjects were the students in Guangzhou University library, which is a public place with a high population density. The impact of students wearing masks on thermal comfort was significant, which would affect their learning efficiency. Considering the effects of wearing a mask, thermal comfort can be improved by improving the indoor thermal environment. Thus, the objectives of this study was pointed out, as follows.

(1) Determine the impact of wearing masks on the personal comfort of students in Guangzhou University Library.
(2) Analyze the physical discomfort caused by wearing masks.
(3) Establish different thermal comfort models under the conditions of wearing masks and not wearing masks.

2. Methods

The methods of this study are as follows. First, data on the subjects' overall and local (face, head, back, chest, and limbs) perceptions ("votes") of environmental parameters were collected, collated, and analyzed. Second, the indoor thermal comfort index was calculated, neutral temperature was determined using linear regression, while preferred temperature was determined using probit regression. Finally, the acceptable and comfort temperatures were determined by analyzing the perception data and the thermal comfort results. The results of this study can assist in improving the comfort levels of students by adjusting

the T_{op} and can subsequently be used on a large-scale in other public places.

2.1. Research environment

The study was conducted in the Guangzhou University library (Fig. 1). Guangzhou is located in the Pearl River Delta in South China (112°–114.2° E and 22.3°–24.1° N). The library has five floors, among which the first floor was the archival room. Students primarily use the third and fourth floors for self-study. The fifth floor is also used by few students, but because of the transparent roof, the ambient temperature of this floor is generally higher than that of the lower floors. To expand the temperature range observed in the study, third, fourth, and fifth floors were selected for further investigation. The study period was June 2021. As shown in Fig. 2, based on the data from the Guangzhou Meteorological Station, the average temperature reached 30 °C in Guangzhou in June; the maximum outdoor temperature reached 37 °C, and average relative humidity (RH) ranged between 70% and 95%. Therefore, most people feel uncomfortable in outdoor environments during this month.

2.2. Subjective survey and measurements

A total of 1602 healthy college students (550 males and 1052 females; detailed information is provided in Table 1) were randomly invited to participate in the survey. The field survey were conducted in accordance with the ethical standards of the Declaration of Helsinki, and informed consents were obtained from all participants. When they agreed, their health status needs to been record, including having a fever, cough, sore throat, or chronic disease et al. And then, the participants start to answer the questionnaires. In this investigation, the subjects were all of health students. Before they answered the questionnaire, they need to indicate their heath condition, except any discomfort for masks. Meanwhile we suggest that when filling in the questionnaire, the subjects only consider that the factor causing their discomfort is wearing masks. In addition, all of the subjects were request to keep to seat in library exceeding half hour. Liu et al. [33] found that when people enter a cold or hotter environment, the skin temperature was stable after 10–20 min. Huizenga et al. [34] found that the human core temperature and head temperature were balanced within 30 min. In other previous studies [35–37], 20–30 min of experimental preparation time was also adopted. Therefore, this study was conducted on these basis to ensure that the subjects were in thermal equilibrium and had not just entered the library. The filling time of each questionnaire last 3–4 min. The fluctuation range of temperature and humidity in the library were small. Thus, the measurement and field survey were reasonable. The testing subjects were presented in Fig. 3. The average age of the subjects was 20.7 years. The clothing insulation values were estimated based on ASHRAE standard 55 [38]. They were wearing short sleeved T-shirts (0.08 clo), thin trousers (0.15 clo), skirt (0.14/0.23 clo), bra (0.01 clo), panties (0.03 clo), men's briefs (0.04 clo), socks (0.02 clo), and shoes (0.02 clo) et al. The average total clothing insulation (Icl) was 0.39 clo during the test.

A written, self-completed questionnaire, consisting of two parts, was used to survey the participants. The first part investigated subjective votes on the thermal sensation (TSV), air movement sensation (ASV), and humidity sensation (HSV) using the scales shown in Table 2. The second part investigated whether students wore masks, whether they experienced any symptoms of discomfort, and assessed the duration of wearing masks. The scales of the subjective vote were in accordance with the thermal environment comfort levels described in the ASHRAE Standard 55 [40] and ISO 7726 [41].

2.3. Measured parameters and instruments

Environmental parameters (listed in Table 3) were measured every

Fig. 1. Testing site.
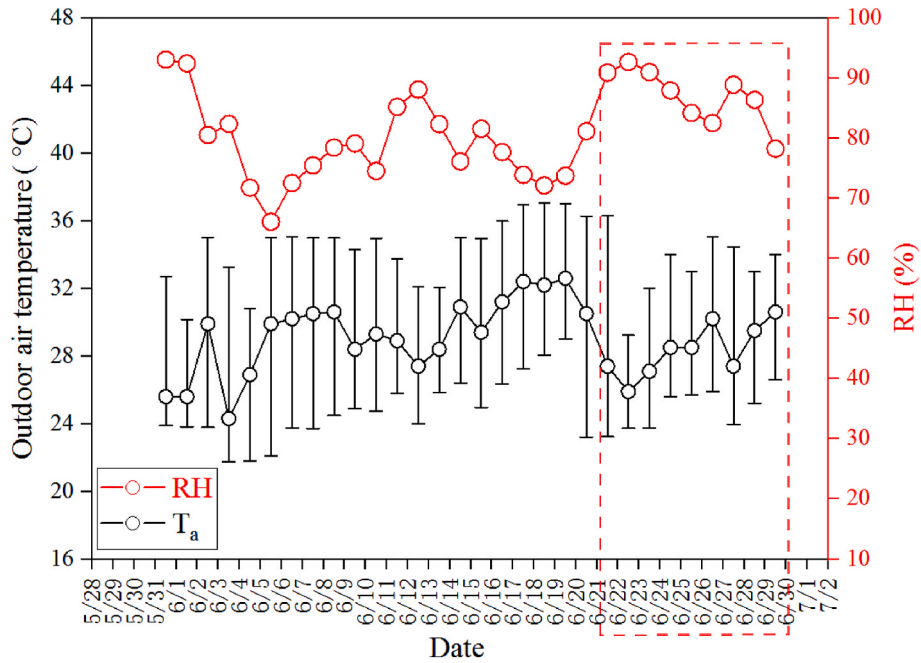
Fig. 2. Outdoor daily air temperature variation range and daily average relative humidity in Guangzhou in June 2021.

Table 1

Anthropometric data of subjects (SD: standard deviation).

Sex	Number	Age in years (SD)	Height in m (SD)	Weight in kg (SD)	Body surface area in m^2 (SD)[a]	Ponderal index in kg$^{1/3}$m^{-1} (SD)[b]	I_{cl} in clo (SD)
Male	550	20.9 (1.51)	1.73 (0.06)	62.7 (7.95)	1.74 (0.12)	2.29 (0.09)	0.35 (0.11)
Female	1052	20.6 (1.57)	1.61 (0.05)	50.2 (6.02)	1.50 (0.10)	2.28 (0.08)	0.41 (0.12)
Total	1602	20.7 (1.56)	1.65 (0.08)	54.5 (9.00)	1.58 (0.15)	2.29 (0.08)	0.39 (0.12)

[a] Body surface area (A) was determined using the DuBois area: A = 0.202 w$^{0.424}$h$^{0.725}$ [39], where w is the weight and h is the height.

[b] Ponderal index = w$^{1/3}$/h.

Fig. 3. Testing subjects.

Table 2
Subjective vote scale.

Thermal sensation	Air movement sensation	Humidity sensation	Thermal preference	Air movement preference	Humidity preference	Thermal Acceptability
−3 cold	−3 much too weak	−3 very dry				
−2 cool	−2 too weak	−2 dry				
−1 slightly cool	−1 slightly weak	−1 slightly dry	−1 lower	−1 lower	−1 lower	
0 neutral	0 just right	0 neutral	0 no change	0 no change	0 no change	0 acceptable
+1 slightly warm	+1 slightly strong	+1 slightly wet	+1 higher	+1 higher	+1 higher	+1 unacceptable
+2 warm	+2 too strong	+2 wet				
+3 hot	+3 much too strong	+3 very wet				

Table 3
Instruments used to measure the air temperature (T_a), relative humidity (RH), globe temperature (T_g), air velocity (V_a).

Equipment	Model	Parameter	Measuring range	Accuracy	Sampling rate
Thermal comfort instrument	SSDZY-1	T_a (°C)	−20–80 °C	±0.3 °C	30 s
		RH (%)	0.01–99.9%	±2% (10–90%)	30 s
		T_g (°C)	−20–80 °C	±0.3 °C	30 s
Universal air velocity recorder	WFWZY-1	V_a (m/s)	0.05–5.00 m/s	5% ± 0.05 m/s	30 s

30 s during the survey using an SSDZY−1 thermal comfort meter (Table 3). According to the ISO 7726 guidelines [41], test instruments (described in Section 2.3) were placed near the seats (to increase the accuracy of measurement) at a height of 1.1 m near the head or face of the subjects in a sitting position. In many indoor thermal comfort studies [42–46], the height of the instrument were chose at the level of 1.1 m. When the human body is sitting still, the height of the head or face is about 1.1 m. These parts can be in direct contact with the environment for heat exchange. The sensitivity of the head and face is relatively strong [47–52]. Thus, in this field survey, the height of the instrument was set at level of 1.1 m. A standard globe thermometer with a diameter (*D*) of 0.15 m that was painted matt black (globe emissivity, $\varepsilon_g = 0.95$) was used to measure the globe bulb temperature. The mean radiant temperature (T_{mrt}) was calculated using Eq. (1) [22]:

$$T_{\mathrm{mrt}} = \left\{ \left(T_g + 273 \right)4 + \left[\frac{\left(1.1 \times 10^8 \times V_a^{0.6} \right)}{\left(\varepsilon_g \times D^{0.4} \right)} \right] \times \left(T_g - T_a \right) \right\}^{1/4} - 273 \tag{1}$$

where T_a is the ambient temperature, T_g is the globe temperature, and V_a is the air velocity.

2.4. Data processing

Healthy subjects were selected to ensure the validity of the data, and incomplete questionnaires were excluded. *PMV* and *SET** were calculated using the CBE Thermal Comfort Tool (http://comfort.cbe.berkeley.edu/). *SET** can be adjusted according to differences in clothing and can unify the data of different experimental conditions into the same dimension for comparative analysis. Selecting *SET** as the thermal environment index could minimize the impact of the inability to control clothing in this study [52,53]. The T_{op} was calculated according to the conditions presented in the ASHRAE Standard 55 normative [38]. Linear regression and logistic regression were used to analyze the relationship between the environmental parameters and the responses to the subjective questionnaire. All statistical analyses (including figures and charts) were performed using IBM SPSS Statistics 23 (IBM, Inc., Armonk, NY, USA), Excel (Microsoft, Redmond, WA, USA), and Origin 2021 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Thermal parameters

The observations of the measured indoor thermal parameters (T_a, RH, V_a, and T_{mrt}) measured are summarized in Table 4. The mean T_a, RH, and V_a were 27.7 °C, 79.2%, and 0.17 m/s respectively. The minimum RH of the air in the library reached 74.1%, indicating that the overall humidity in the library was relatively high, which is related to the climate of Guangzhou [39]. Based on our calculations, the minimum (maximum) values of *PMV* and T_{op} were −1.28 (2.19), and 25.9 °C (31.2 °C), respectively.

The distribution of environmental parameters in the library is shown in Fig. 4. T_{op} in the library was mostly (81.2%) between 26 °C and 29 °C. Owing to the influence of solar radiation, the fifth floor of the library showed the highest temperature. The *RH* ranged mostly between 76% and 82%, which is consistent with the outdoor relative humidity. The proportion of indoor V_a less than 0.4 m/s was high (92.9%), and the perception of air blowing was not strong.

3.2. Effect of wearing masks on human comfort

Among the 1602 questionnaires collected, 1112 questionnaires of subjects who wore masks were included. Among them, 822 (73.9%) subjects indicated that wearing masks made them uncomfortable. The voting distribution for discomfort regarding each body part is shown in Fig. 5. The proportion of facial discomfort was the largest (71.0%), and was related to direct contact between the human body and the mask. The proportions of head and chest discomfort were 19.2% and 18.3%, respectively. Wearing masks for a long time may cause headache, dyspnea, and other symptoms; therefore, the proportions of discomfort due to these two symptoms would increase over time. As shown in Fig. 6, the symptoms most frequently voted by the subjects were facial heat (62.7%), followed by dyspnea (25.4%). Some subjects who wore masks for a long time experienced rapid heartbeat (9.1%) and nausea (4.1%), and a small number felt dizzy and weak (7.9%), or reported blurry vision (1.3%).

3.3. Effect of wearing mask on thermal preference

Fig. 7 shows the thermal preference of subjects to environmental parameters with and without masks. A greater proportion of subjects with masks preferred a higher air velocity than that of subjects without wearing masks. Additionally, the more than half subjects preferred reduced the operative temperature to improve thermal comfort, specially the subjects with masks. Thus, effects of masks on thermal comfort are significant. The demands of air velocity and operative temperature was different between wearing masks and without wearing masks. In addition, most subjects opined that the humidity level was acceptable. The primary reason is that the subjects has strong adaptive

Table 4
Indoor thermal parameters.

| Parameters	Abbreviation (units)	Minimum	Maximum	Mean	Standard deviation
Air temperature	T_a (°C)	25.9	31.1	27.7	1.15
Relative humidity	RH (%)	74.1	85.2	79.2	1.98
Air velocity	V_a (m/s)	0.01	0.80	0.17	0.16
Mean radiant temperature	T_{mrt} (°C)	25.8	31.4	27.6	1.04
Operative temperature	T_{op} (°C)	25.9	31.2	27.6	1.10
Predicted Mean Vote	PMV (-)	−1.28	2.19	0.45	0.49
Predicted Percentage Dissatisfied	PPD (%)	5.0	81.9	14.2	12.93
Standard Effective Temperature	SET (°C)	21.8	33.9	26.6	1.78
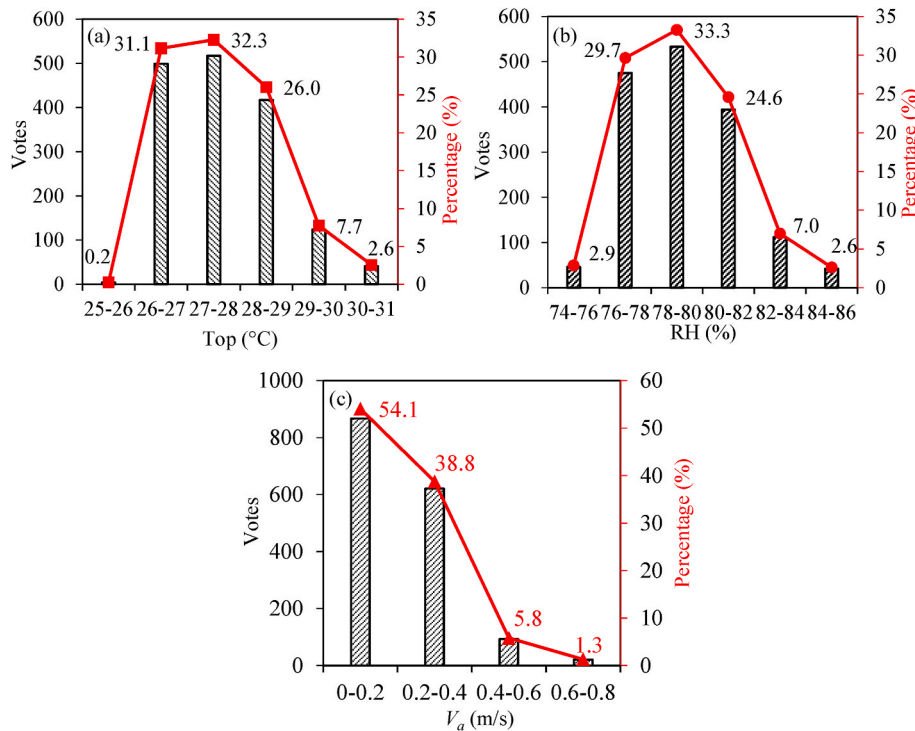
Fig. 4. Distribution of indoor environmental parameters in the library: (a) T_{op}; (b) RH; and (c) V_a.
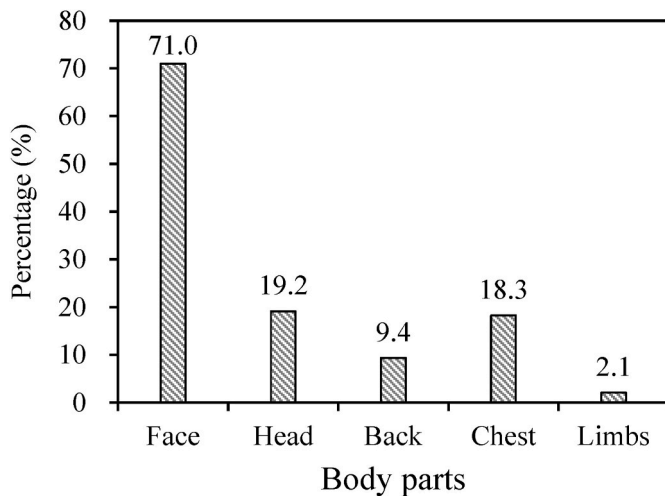

Fig. 5. Percentages of participants who voted that they experienced discomfort in various body parts.

ability in high relative humidity in South China [54–56]. Therefore, in order to improve the thermal comfort in an air-conditioned room, the operative temperature needs to be lower with higher air velocity.

3.4. Distribution of thermal sensation vote

The overall and local TSV results showed that wearing masks has a certain impact on human thermal sensation (Fig. 8(a–f)). The proportion of subjects wearing masks who reported TSV greater than zero was approximately 6.7% greater than among those not wearing masks. Considering individual parts of the body, the most obvious change in the TSV was in the face, where the percentage of subjects wearing masks and reporting a TSV greater than zero increased by approximately 11.4%. The proportion of subjects who wore masks and reported a TSV greater than zero for the head and chest were 6.5% and 5.8%, respectively. Further, the proportion of subjects who wore masks and reported a TSV greater than zero for the back and limbs was small. Wearing masks can affect the breathing frequency and inspiratory capacity, thereby resulting in heat accumulation on the face, and an overall feeling of excessive heat.

Fig. 9 shows the distribution of the TSV and ASV on the whole body and various body parts, in the form of box plots. No difference was observed between those with and without masks in their voting on the feeling of heat and wind on the back, chest, and limbs. The most obvious
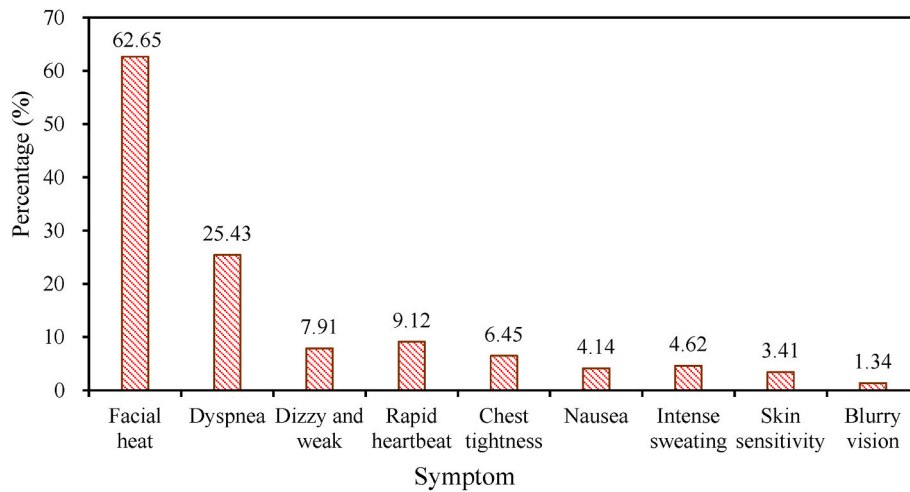
Fig. 6. Distribution of the percentage of symptoms among participants wearing masks.
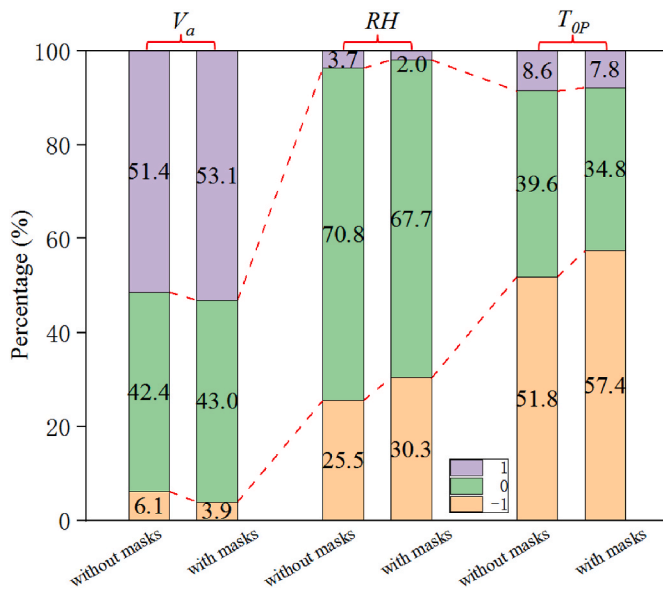

Fig. 7. Distribution of percent thermal preference for environmental parameters with or without masks. −1: lower; 0: no change; and +1: higher.

differences between the subjects who wore and did not wear masks were in their reporting about the face and head. In the subjects who wore masks, the mean TSV (MTSV) of the face and head was greater than those who did not wear masks, and the mean ASV (MASV) decreased. For the whole body MTSV, similar differences were observed between the subjects who wore and did not wear masks.

These correlations were calculated based on thermal sensation voting. Fig. 9 shows that the correlation coefficient between wearing masks and not wearing masks is low, which indicates that they have no correlation. The results were reasonable. The small p-value indicates that there is a significant difference between them, which indicates that there is a significant difference between wearing masks and not wearing masks in the whole thermal sensation and some local thermal sensation.

In this investigation, due to the air condition, the indoor air temperature ranged from 26 °C to 29 °C. Most subjects always feel acceptable in whole body thermal sensation. In addition, the comfort temperature was determined by the whole body thermal sensation. Thus, the difference of comfort temperature between masks and no masks were not significant. However, from Figs. 8 and 9, mask mainly affects the face and head of the human body, resulting in higher

requirements for the comfort of the environment as a whole., especially wearing the mask for a long time. Therefore, it is very necessary to control environmental parameters for human local thermal sensation and whole body thermal sensation.

3.5. Correlation analysis of MTSV and T_{op}/SET

The average TSV was calculated within 1 °C intervals of T_{op}/SET*. Regression equation was used to calculate neutral T_{op}/SET*. As shown in Fig. 10, for subjects without masks, when MTSV was 0 °C, T_{op} was 26.5 °C and SET* was 25.3 °C; moreover, for subjects wearing masks, when MTSV was 0, T_{op} was 26.2 °C and SET* was 25.0 °C. The neutral T_{op}/SET* of the environment was 0.3 °C lower for subjects wearing masks than for subjects without masks.

3.6. Preferred temperature

The subject's actual thermal preference vote in the subjective questionnaire and the corresponding T_{op}/SET* were subjected to probit regression analysis, and the curves of the subject's preferred temperature increase and decrease, and the T_{op}/SET* were obtained. The T_{op}/SET* corresponding to the intersection of the two curves represented the subject's preferred T_{op}/SET*. The probability curves are shown in Fig. 11 (a–d). The preferred T_{op} of the subjects without masks was 27.0 °C, and that of subjects with masks was 0.5 °C lower at 26.5 °C. The preferred SET* of the subjects without masks (with masks) was 25.5 °C (25.0 °C).

Many previous investigations also found that the neutral temperature was higher than the preferred temperature [25,55–59]. However, in some previous investigations, the preferred temperature is equal to or higher than the neutral temperature [60,61]. For example, Tewari et al. [60] found that in Indian office buildings, the comfortable temperature was 28.8 °C higher by 0.7 °C than the neutral temperature 28.1 °C. Zheng et al. [61] found that the values of neutral SET* and preferred SET* were 25.6 °C in prefab construction site offices. In addition, some previous investigations show that the regression method were used to analyze the subjects' behavioral adaptation [62–64]. In hot summer and warm zoom, human have strong adaptability of hot thermal environment. In air-conditioned indoor thermal environment, the set temperature always lower than nature ventilation condition. The subjects were trained in cooler indoor thermal environment. Thus, the neutral comfort temperature was lower than preferred temperature.

3.7. Acceptable temperature zone and comfort temperature zone

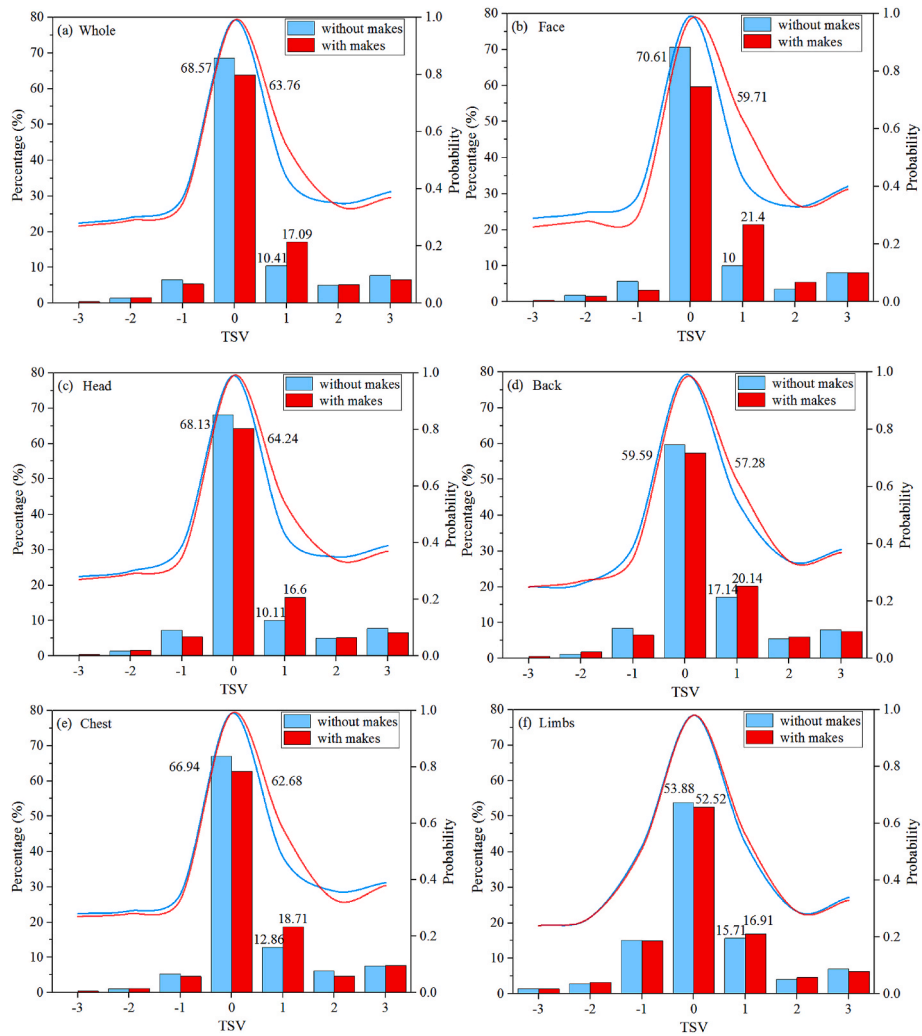The percentage (PD) of items on the questionnaire voted as

Fig. 8. Percentage distribution and normal distribution curve of thermal sensation votes in the library: (a) Whole; (b) Face; (c) Head; (d) Back; (e) Chest; and (f) Limbs. The votes were scaled as: −3: cold; −2: cool; −1: slightly cool; 0: neutral; +1: slightly warm; +2: warm; +3: hot.
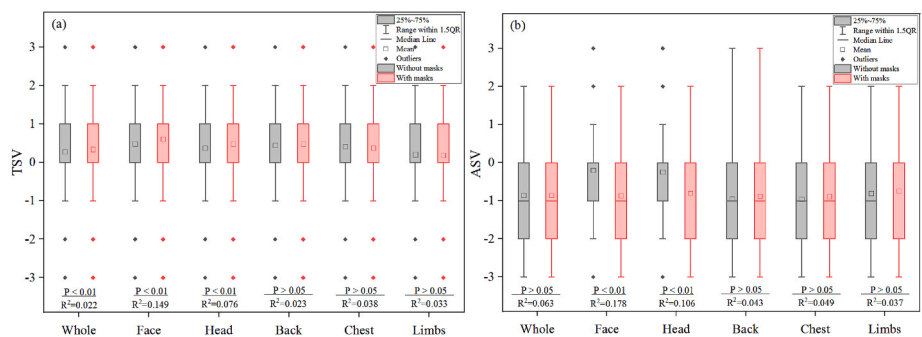

Fig. 9. Box plot for (a) thermal sensation vote and (b) air movement sensation vote.

unacceptable per person was regressed with the T_{op} and SET^* of the corresponding time point and the results are shown in Table 5 and Fig. 12(a and b). When PD was 20%, an acceptable temperature zone was obtained, and when PD was 10%, a comfort temperature zone was obtained. As shown in Table 5, the zone of acceptable T_{op} according to PD was 23.7–28.9 °C, and the comfort zone was 24.8 °C–27.7 °C without masks. The acceptable temperature zone obtained from SET^* was 22.8–29.0 °C, and the comfort zone was 24.4–27.6 °C. Contrastingly, the acceptable temperature zone obtained by PD was 22.3–27.6 °C and the comfort zone was 24.0–27.2 °C without masks. The temperature range

calculated by T_{op} was narrower than that of SET^*, and the actual acceptable temperature zone and comfort temperature zones were wider. In addition, wearing a mask shifted the acceptable temperature and comfort temperature zones to a lower temperature.

3.8. Acceptable duration of wearing masks

According to the voting statistical distribution of subjects' expected duration of wearing masks, more than 75% expected to wear masks for 2.0 h or less (as shown in Fig. 13), and only few subjects could tolerate
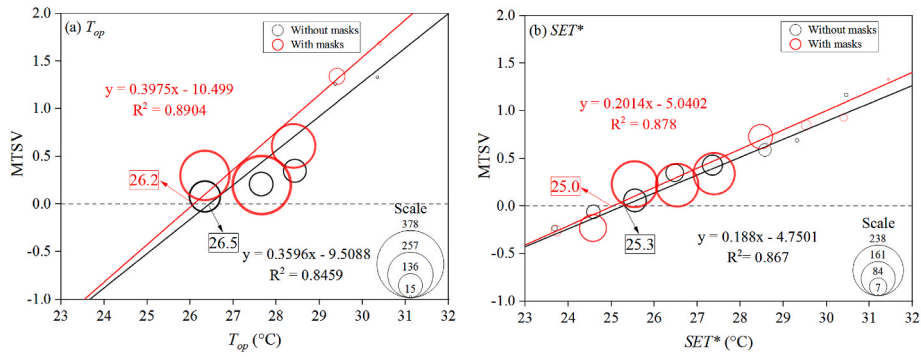
Fig. 10. Relationship between T_{op}/SET^* and MTSV: (a) T_{op}; and (b) SET^*.
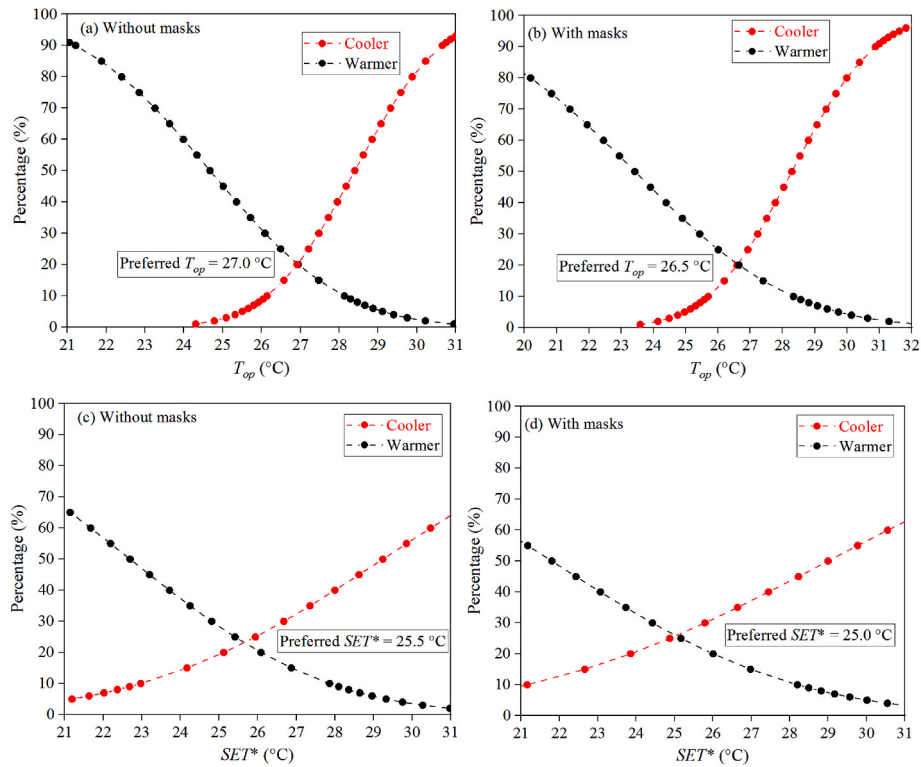

Fig. 11. Probit analysis of preferred T_{op}/preferred SET^*:(a)Without masks, (b)With masks.

Table 5
Unacceptable percentage of Operative temperature under different conditions.

Condition	Equation y = PD x = T_{op}/SET^*	Acceptable temperature range (°C)	Comfort temperature range (°C)
Without masks	$y = 2.2063x^2 - 115.97x + 1529.3$ (T_{op})	23.7–28.9	24.8–27.7
	$y = 1.3999x^2 - 72.662x + 949.41$ (SET^*)	22.8–29.0	24.4–27.6
With masks	$y = 2.0164x^2 - 104.28x + 1355$ (T_{op})	23.3–28.4	24.6–27.1
	$y = 1.2547x^2 - 64.158x + 827.98$ (SET^*)	22.3–28.8	24.0–27.2

more than 3 h of wearing masks. The longer the duration for wearing masks, the wetter the face will be, thereby reducing the comfort of the human body. Most people experienced increased physical discomfort after exceeding their "acceptable duration," which affected their work and learning efficiency.

4. Discussion

4.1. Effect of wearing face masks on human thermal comfort

Wearing masks while traveling, and in work and study places has become a daily part of people's lives [65]. The discomfort accompanied by wearing masks has also attracted attention [66–68]. In the study or work place, wearing a mask for a long time may lead to a certain degree of physical symptoms. While wearing masks, people need a more comfortable environment to reduce the thermal discomfort caused by masks. Subsequently, people often remove their masks to alleviate their discomfort, which reduces work efficiency [68,69]. The inner layer of a mask that has been worn for a long time gets wet because of
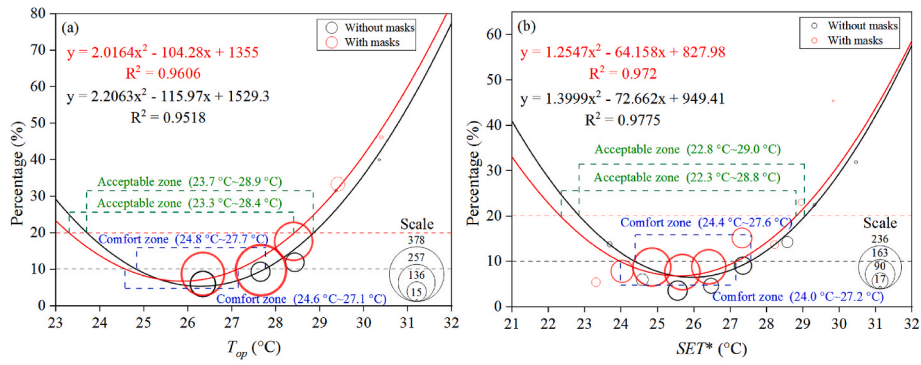
Fig. 12. Relationship between subjective thermal unacceptable percentage and thermal indices: (a) T_{op}; (b) SET^*.
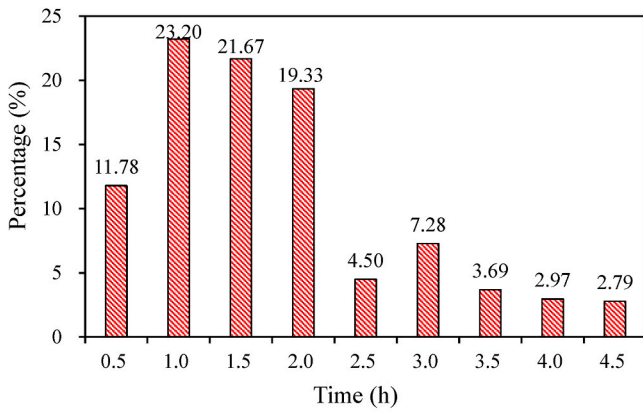

Fig. 13. Distribution of percent "acceptable duration" for wearing masks.

condensation of the water vapor generated by breathing and sweat evaporation [16,68]. People usually do not change masks regularly, and continue wearing the same mask for a long time, which affects both hygiene and comfort. This study found that people who wore masks preferred increased air velocity, especially to alleviate the discomfort on the head and face. As shown in Fig. 8(b), the MASV for the face and head of subjects who did not wear masks was close to 0, while that of people who wore masks was one degree lower. The mask, which is in direct contact with the head and face, not only hinders the evaporation and heat dissipation from the head and face but also breathing, which explains the large proportion of chest discomfort. Therefore, fever and redness on the face and dyspnea were the most prevalent symptoms that were reported after wearing a mask for a long time. According to Fig. 13,

we recommend wearing a disposable face mask for no more than 2 h to minimize discomfort.

4.2. Adaptive analysis of the operative temperature

To analyze whether the regression equations of MTSV and T_{op} obtained in this study were adaptive, we compared the results of this study with those of previous studies. Table 6 summarizes the relationship between the MTSV and the thermal indices in summer. Different regression equations were obtained in different places, and the calculated neutral temperatures were also different. In summer, for Guangdong, the neutral temperature of Guangzhou [56,70] differed from that of Shenzhen [55]. The neutral temperature in Shenzhen was 25.0 °C, while that reported for Guangzhou were 26.2 °C, 26.8 °C, and 26.5 °C (26.2 °C). The acceptable temperature range was 22.9–29.6 °C in a prefabricated site office in Guangzhou and 20.2–29.4 °C for office staff in Shenzhen. In this study, the acceptable temperature range was 23.7–28.9 °C (23.3–28.4 °C). This difference could be possibly because prefabricated site offices are mainly used for construction workers, and their heat resistance is greater than that of people working in regular offices [44,54,55,72–74]. A study in Shenzhen reported that as people wear more layers of clothes when the ambient temperature is low, which increases their thermal resistance, they adapt to a large temperature range [55]. The neutral SET^* values in two previous Guangzhou studies were 25.6 °C [70] and 26.18 °C [68], respectively, while the neutral SET^* value obtained in this study was 25.3 °C (25.0 °C), which was associated with the clothing habits of the subjects. Further, wearing masks lowered the neutral temperature value, and the acceptable and comfort temperature ranges shifted to the left.

Table 6
Comparison of the TSV model with previous studies conducted in offices.

Author	Place	Neutral T/SET^* (°C)	Linear regression equation	Acceptable temperature zone (°C)	Building type
This study	Guangzhou	26.5	MTSV $= 0.3975\,T_{op} - 10.499$	23.7–28.9	Library (Without masks)
		26.2	MTSV $= 0.3596\,T_{op} - 9.5088$	23.3–28.4	Library (With masks)
		25.3	MTSV $= 0.188\,SET^* - 4.7501$	22.8–29.0	Library (Without masks)
		25.0	MTSV $= 0.2014\,SET^* - 5.0402$	22.3–28.8	Library (With masks)
Fu et al. [56]	Guangzhou	26.2	MTSV $= 0.301\,T_{op} - 7.902$	22.9–29.6	Prefab site office
Wu et al. [60]	Guangzhou	26.8	TSV $= 0.2796\,T - 7.5009$	/	Office
Yang and Zhang [71]	Changsha	27.7	TSV $= 0.32\,T_{op} - 9.12$	25.1–30.3	Residential/Office
Luo et al. [55]	Shenzhen	25.0	TSV $= 0.203\,T_{op} - 5.077$	20.2–29.4	Office
Indraganti et al. [72]	Tokyo	27.1	TSV $= 0.299\,T - 8.109$	/	Office
Indraganti et al. [44]	Hyderabad	26.1	TS $= 0.194\,T_g - 5.103$	/	Office
	Chennai	27.0	TS $= 0.110\,T_g - 3.029$	/	Office
Zheng et al. [61]	Guangzhou	25.6	MTSV $= 0.2381\,SET^* - 6.1052$	21.1–31.9	Office
Ji et al. [58]	Guangzhou	26.18	TSV $= 0.2345\,SET^* - 6.1403$	/	Office
Dhaka and Mathur [25]	Jaipur	26.36	TSV $= 0.183\,SET^* - 4.824$	/	Office
Tewari et al. [60]	Jaipur	24.62	TSV $= 0.26\,SET^* - 6.4$	/	Office

4.3. Limitations

During this survey, the outdoor environment was hot and humid while the indoor RH ranged between 74% and 86%; hence, a good humidity gradient could not be formed; additionally, the subjects' voting on RH also showed strong acceptability. Therefore, the influence of humidity on thermal sensation was not analyzed in this study. In addition, the instrument for measuring environmental parameters was placed at a height 1.1 m above the floor, which is close to the horizontal position of the head when the human body is sitting; hence, it was impossible to specifically analyze the impact of various other environmental parameters on different parts of the body.

We suggest that when filling in the questionnaire, the subjects only consider that the factor causing their discomfort is wearing masks. Of course, the causes of discomfort also include air quality and environmental parameters, which need to be considered in big data research and need to be paid attention to in future research. Therefore, we could only make a general comparison based on the existing voting data to analyze the sensitivity of each body part to the thermal environment in the study area. Additionally, we only analyzed the comfort of the Operative temperature as a whole without masks and with masks. In addition, subjects of different genders also have an impact on the value of thermal indicators [75]. In this experiment, female subjects are about twice as much as male subjects, so the neutral temperature and comfort temperature may be biased towards female needs.

5. Conclusions

In the summer of 2021, a field test and a questionnaire survey were conducted in a university library in Guangzhou, China. By analyzing the perceived thermal sensations and the thermal index of each parameter under the different environmental conditions for subjects with and without masks, the following results were obtained:

(1) The subjects wearing masks had higher requirements for environmental comfort, and the thermal discomfort in their face and head increased. More than 70% of the subjects wearing masks experienced discomfort on their faces. Among the subjects who felt uncomfortable, 62.7% showed facial fever as a main symptom, while others showed symptoms of dyspnea (25.4%) and rapid heartbeat (9.1%).

(2) For subjects without masks, the neutral T_{op} was 26.5 °C and the preferred T_{op} was 27.0 °C, while the neutral SET^* was 25.3 °C and the preferred SET^* was 25.5 °C. For subjects with masks, the neutral T_{op} was 26.2 °C and the preferred T_{op} was 26.5 °C, while the neutral SET^* was 25.0 °C and the preferred SET^* was 25.0 °C. The neutral T_{op} (SET^*) difference was 0.3 °C and the preferred T_{op} (SET^*) difference was 0.5 °C.

(3) For subjects without masks, the acceptable T_{op} range was 23.7 °C–28.9 °C, and the comfort T_{op} ranged from 24.8 °C to 27.7 °C, while the acceptable SET^* zone ranged from 22.8 °C to 29.0 °C and the comfort SET^* zone range was 24.4–27.6 °C. For subjects wearing masks, the acceptable T_{op} ranged from 23.3 °C to 28.4 °C, and the comfort T_{op} ranged from 24.6 to 27.1 °C, while the acceptable SET^* was 22.3–28.8 °C, and the comfort SET^* ranged from 24.0 °C to 27.2 °C. In summary, the subjects who wore masks preferred colder temperatures.

(4) The difference in thermal comfort between those wearing masks and those not wearing masks is not very big. However, wearing mask for a long time may cause discomfort. Considering the thermal comfort, it is recommended to wearing a mask for no more than 2 h.

CRediT authorship contribution statement

Tianwei Tang: Writing – original draft, Methodology, Data curation. **Yongcheng Zhu:** Formal analysis, Data curation. **Xiaoqing Zhou:** Supervision, Writing – review & editing. **Zhisheng Guo:** Investigation. **Yudong Mao:** Investigation. **Huilin Jiang:** Resources. **Zhaosong Fang:** Writing – review & editing, Methodology, Conceptualization. **Zhimin Zheng:** Data curation, Writing – review & editing. **Xiaohui Chen:** Writing – review & editing, Visualization.

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.

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Appendix

Library human thermal comfort survey questionnaire

Age_____   Sex_____   Height_____   Weight_____

Date :_____/_____/_____Time :_____:_____am/pm

Part 1: Your current dress and accessories

Top: □ vest □ short sleeved shirt, short T shirt □ long sleeved shirt □ long T shirt □ slim skirt (sleeveless)

   □ thick dress (sleeve) □ dress □ Other_____

Below: □ trousers / thin pants □ shorts □ sports pants □ jeans □ long skirt □ short skirt □ other_____

Foot: □ sneakers □ leather shoes □ sandals □ slippers □ cloth shoes □ stockings □ socks

Part 2: Your activity mode: □ sit □stand

Part 3: Subjective evaluation

3.1 Evaluation of thermal sensation

Whole: □ 3 cold □ 2 cool □ 1 slightly cool □ 0 neutral □ 1 slightly warm □ 2 warm □ 3 hot

Face: □ 3 cold □ 2 cool □ 1 slightly cool □ 0 neutral □ 1 slightly warm □ 2 warm □ 3 hot

Head: □ 3 cold □ 2 cool □ 1 slightly cool □ 0 neutral □ 1 slightly warm □ 2 warm □ 3 hot

Back: □ 3 cold □ 2 cool □ 1 slightly cool □ 0 neutral □ 1 slightly warm □ 2 warm □ 3 hot

Chest: □ 3 cold □ 2 cool □ 1 slightly cool □ 0 neutral □ 1 slightly warm □ 2 warm □ 3 hot

Limbs: □ 3 cold □ 2 cool □ 1 slightly cool □ 0 neutral □ 1 slightly warm □ 2 warm □ 3 hot

3.2 Experience of airflow (wind)

➢ Subjective feelings of the airflow grade

Whole: □ much too weak □ much too weak □ slightly weak □ neutral □ slightly strong □ too strong □ much too strong

Face: □ much too weak □ much too weak □ slightly weak □ neutral □ slightly strong □ too strong □ much too strong

Head: □ much too weak □ much too weak □ slightly weak □ neutral □ slightly strong □ too strong □ much too strong

Back: □ much too weak □ much too weak □ slightly weak □ neutral □ slightly strong □ too strong □ much too strong

Chest: □ much too weak □ much too weak □ slightly weak □ neutral □ slightly strong □ too strong □ much too strong

Limbs: □ much too weak □ much too weak □ slightly weak □ neutral □ slightly strong □ too strong □ much too strong

➢ Overall evaluation of the airflow intensity
□ Acceptable (0) □ Unacceptable (1)
➢ Expectations for wind speed
□ lower (-1) □ no change (0) □ higher (1)

3.3 Feeling of humidity (sultry feeling)

➢ Subjective feelings of the humidity levels

Whole: □ very dry □ dry □ slightly dry □ neutral □ slightly wet □ wet □ very wet

Face: □ very dry □ dry □ slightly dry □ neutral □ slightly wet □ wet □ very wet

Head: □ very dry □ dry □ slightly dry □ neutral □ slightly wet □ wet □ very wet

Back: □ very dry □ dry □ slightly dry □ neutral □ slightly wet □ wet □ very wet

Chest: □ very dry □ dry □ slightly dry □ neutral □ slightly wet □ wet □ very wet

Limbs: □ very dry □ dry □ slightly dry □ neutral □ slightly wet □ wet □ very wet

➢ Overall evaluation of the humidity
□ Acceptable (0) □ Unacceptable (1)
➢ Expectations of humidity
□ lower (-1) □ no change (0) □ higher (1)

. (*continued*).

3.4 Overall evaluation of the environment

□ Acceptable (0) □ Unacceptable (1)

3.5 Expectations for the environment

□ colder (1) □ no change (0) □ warmer (1)

3.6 Evaluation of indoor air quality

□ Acceptable (0) □ Unacceptable (1)

Part 4: Wearing masks

4.1 Whether you are wearing a mask

□ is □ no

4.2 If wearing a mask, the mask type is:

□ General masks □ Medical surgical mask □ N95 mask

4.3 Time to wear a mask:

□ 0 hours □ 0.5 hours □ 1.0 hours □ 1.5 hours □ 2.0 hours

□ 2.5 hours □ 3.0 hours □ 3.5 hours □ 4.0 hours □ >4.0 hours

4.4 Does wearing a mask make you feel some uncomfortable?

□ yes □ no

4.5 Hot and uncomfortable parts: (multiple choice)

□ Face □ Head □ Back □ Chest □ Limbs

4.6 What specific are caused by wearing a mask: (multiple choice)

□ Facial heat □ Dyspnea □ Dizzy and weak □ Rapid heartbeat □ Chest tightness □ Nausea

□ Intense sweating □ Systemic fatigue □ Skin sensitivity □ Blurry vision □ other_____

4.7 Acceptable duration of wearing masks:

□ 0 hours □ 0.5 hours □ 1.0 hours □ 1.5 hours □ 2.0 hours

□ 2.5 hours □ 3.0 hours □ 3.5 hours □ 4.0 hours □ >4.0 hours

. (*continued*).

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