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Research Article

Effects of mask wearing duration and relative humidity on thermal perception in the summer outdoor built environment

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Abstract

During the pandemic, face masks are one of the most significant self-protection necessities, but they also cause heat stress. By using the ERA5 (ECMWF Reanalysis 5th Generation) database and the local weather bureau data, the effect of mask wearing on outdoor thermal sensation has been investigated by a survey conducted in the hot summer and cold winter region of eastern China in the summer of 2020. Results show that wearing a face mask for a longer period result in a higher level of discomfort, and the primary source of discomfort is hot and stuffy feelings. The effect of relative humidity is crucial for mask wearers in warm-biased thermal environments, as mean thermal sensation vote (TSV) peaks when environmental relative humidity reaches the range of 70% to 80% and decreases after this range due to the evaporation within the microclimate created by a face mask. Meanwhile, prolonged mask wearing increases participants' hot feelings, especially in warm environments. Specifically, participants wearing face masks for less than 30 min feel hot at a physiological equivalent temperature (PET) value of 34.4 °C, but those who wear them for over 60 min express hot feelings even at a PET value of 24.7 °C. The participants who wear a face mask while walking slowly outdoors have similar thermal sensations to those who do not wear a mask, but are in a higher activity level. The findings demonstrate that mask wearing has a crucial impact on outdoor thermal comfort assessment in a warm-biased outdoor thermal environment.

Keywords
outdoor thermal comfort;
disposable medical masks;
mask wearing duration;
relative humidity;
physiological equivalent temperature (PET)

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1 Introduction

Livable outdoor spaces allow city residents to enjoy leisure, entertainment, and exercise while alleviating their mental pressure and promoting their health and well-being (Abraham et al. 2010; Bélanger et al. 2019). The key to achieving this goal in high-density cities is creating a healthy and comfortable outdoor space (Lai et al. 2020a; You and Ding 2021; Zhong et al. 2022a). Human thermal comfort is defined as a psychological state in which people are satisfied with the thermal environment (ASHRAE 2020), indicating that thermal comfort is influenced mainly by environmental and individual factors. Specifically, physical, physiological and psychological factors are direct factors, and behavioral, personal, social and cultural factors, as well as thermal history, location and alliesthesia, heterogeneity are indirect factors (Lai et al. 2020b; Peng et al. 2021; Wu et al. 2021). The influence of physical factors on outdoor thermal comfort, especially thermal parameters have been widely investigated by previous studies. According to Tian et al. (2022), half of the existing studies showed that microclimate parameters had the most important effect on human thermal perception, within which, solar radiation and wind are the mainstream investigated parameters. Li et al. (2018) further evaluated outdoor thermal comfort by investigating subjects' perception of solar radiation and wind conditions, revealing their different influences on individuals. Meanwhile, wind and thermal comfort assessment have become points of concern

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at the pedestrian level in the built environment for the recent decades (Zhang et al. 2020; Guo et al. 2022; Zhong et al. 2022b). Zou et al. (2021) investigated the influence of wind turbulence condition by modeling wind effect on convective heat loss for assessing outdoor thermal comfort. By contrast, environmental relatively humidity (*RH*) has been paid less attention. Normally, people are not very accurate at judging changes in *RH* levels unless they are very high or very low and their sensation is coupled with air temperature (Nikolopoulou and Lykoudis 2006). This fact results in a phenomenon that it is still underappreciated in field surveys on outdoor thermal comfort even though it has already been included in the earlier surveys (Zhu et al. 2022). It implies that the effect of environmental humidity on outdoor thermal comfort is not sufficiently understood, and further quantification of this effect is desirable.

In response to COVID-19's outbreak in 2020, urban residents are normally suggested to wear face masks when going outside and gathering in crowded spaces, such as plazas, semi-open malls and parks. Mask wearing presents new changes and challenges for outdoor thermal comfort research. Although the pandemic has already lasted for three years till now, new coronaviruses, delta and omicron, are still active worldwide (Menni et al. 2022). Several recent studies have tried to clarify the transmission routes and minimized the transmission via close contact among people (Morawska et al. 2020; Li et al. 2022). Note that reducing the exposure risks during the daily outdoor activities becomes a significant issue in public health. It is achieved particularly by adopting some simple and effective methods (Dai and Zhao 2023). Face mask, as a typical and portable personal protective equipment, has been proven to effectively reduce exposure to air pollution and prevent the spread of respiratory virus infection (Mueller et al. 2018; Zhou et al. 2018; Dai and Zhao 2020). However, as the physical barrier protective equipment, face mask brings a certain impact on the respiratory process. Particularly, it obstructs the normal breathing process, and part of the exhaled carbon dioxide would be inhaled during each breathing cycle, both of which increase the frequency and depth of breathing (Lazzarino et al. 2020). Meanwhile, Lee and Wang (2011) has also quantified the respiratory obstruction caused by N95 masks, resulted in an increase of resistances of respiratory and expiratory by 126% and 122% on average, respectively, while air exchange rate decreased by 37% on average. Thus, it is reasonable to infer that wearing a face mask might greatly affect the assessment of thermal sensation and comfort.

In fact, wearing face mask is not an entirely new issue in the expertise area of human thermal comfort. For the recent decades, previous studies have reported that the thermal perception of human face is more sensitive than that of other body segments (Nadel et al. 1973). A recent study on the assessment of outdoor thermal comfort has elaborated on this by developing a multi-node thermal regulation and comfort model (Xie et al. 2020). Wearing face mask to some extent hinders the heat exchange between the facial area and the environment, which may affect the overall thermal sensation and comfort of human. Taking N95 mask as an example, there is a significant increase in facial skin temperature under the cover of mask (Roberge et al. 2012). Besides the increase in facial skin temperature, a few indoor experiments have reported that the microclimatic parameters such as air temperature and humidity inside the mask are also the cause of discomfort (Li et al. 2005; Lin and Chen 2019; Zhang et al. 2021). The influences of air temperature and humidity inside the mask on human thermal discomfort are intensified with the increase of mask wearing duration (Shenal et al. 2012). One typical study indicated that the microclimatic parameters affect rapidly the subjects' local thermal sensation of the face during the first 10 minutes of the exercise process, and then continued to develop at a slower rate (Lin and Chen 2019). Nevertheless, the aforementioned thermal comfort studies with face masks are mostly conducted indoors, while the similar experiment and measurement are rarely reported outdoors, particularly the effect of face mask wearing duration on the human thermal response is still unclear in the outdoor environment.

Outdoor thermal comfort can be assessed by the terms of thermal comfort indices. Four indices, predicted mean vote (PMV) (Fanger 1972), standard effective temperature (SET*) (Gagge et al. 1986), physiological equivalent temperature (PET) (Höppe 1999) and universal thermal climate index (UTCI) (Jendritzky et al. 2012), are mainly applied in the outdoor thermal comfort assessment (Potchter et al. 2018). Among which, the PET is the most commonly used indicator evaluating outdoor thermal comfort in previous studies, followed by the UTCI, SET* and PMV according to a recent review by Potchter et al. (2018). The former two were developed for outdoor applications, while the latter two were primarily developed for indoor conditions. Further, because PET, UTCI and SET* are equivalent to temperature values, they are more likely to be applied in a comparison with outdoor thermal comfort studies conducted in different climate regions and conditions (Lin et al. 2013; Pantavou et al. 2013; Zhang et al. 2022a; Zhang et al. 2022b). Specially, in a recent study, the prediction accuracy of PET versus UTCI in relation to different outdoor usage expectations in the post-pandemic era was compared, and PET showed better prediction accuracy than UTCI (Liu et al. 2022). Therefore, PET is a good choice for comparison. The question we are facing is quantifying the effect of mask wearing on thermal sensation based on such an equivalent temperature.

The objective of this study is to examine the influence of wearing a mask on thermal perceptions in an outdoor thermal environment during hot summer by using an online questionnaire survey. This study will answer the following three research questions. (1) How does mask wearing affect people's thermal sensation outdoors? (2) What is the effect of mask wearing duration on thermal perception for outdoor activities? (3) When wearing a face mask, how does environmental relative humidity affect thermal perception?

2 Methodology

2.1 Basic information of online survey

This study was conducted from 14th, August to 24th, September 2020 in Jiangsu Province, China. Jiangsu Province (116°18' E to 121°57' E, 30°45' N to 35°20' N), located in the eastern coastal center of the Chinese mainland, was classified as the hot summer and cold winter climate region according to the Chinese Standard GB 50176 (MOHURD 2016). An online survey regarding thermal perception when wearing a face mask was opened online to residents in Jiangsu Province, mainly in Yangzhou City. The districts of the surveying subjects in this city were also recorded. Rules were set in the survey link to avoid malicious refilling in the survey. An ethical approval by the university academic ethics office had been obtained before the study.

This online survey was designed to investigate the thermal perceptions of face mask wearing outdoors. Basic information, thermal perceptions, and preference for meteorological parameters were included in the survey. In the first part of the survey, the information related to gender, age, height, weight, detailed clothing, activity level, and location information were collected.

Thermal perceptions such as thermal sensation vote (TSV), thermal comfort vote (TCV) and preference of thermal parameters were asked in the second part. Details of vote scales were shown in Table 1. Specifically, the ASHRAE's seven-point scale was found to be not adequate for assessing thermal sensation outdoors in a small-scale pilot study before the main survey. An extended nine-point thermal sensation scale was adopted in this study to cover the possible extreme thermal conditions outdoors. The thermal comfort scale followed that was widely adopted in the ASHRAE Global Database II (Földváry Ličina et al. 2018), and the preference scale followed the ASHRAE 55 Standard (ASHRAE 2020). Meanwhile, questions such as the type and wearing duration of face mask, and the current feelings related to mask wearing were also included. Further information about the major questions in the online survey was included in Appendix A.

Table 1 Subjective vote scales in the questionnaire

Vote scale	Thermal sensation	Thermal comfort	Preference of thermal parameters
−4	Very cold		
−3	Cold		
−2	Cool	Very uncomfortable	
−1	Slightly cool	Uncomfortable	Lower
0	Neutral	Neutral	No change
1	Slightly warm	Comfortable	Higher
2	Warm	Very comfortable	
3	Hot		
4	Very hot		

2.2 Local climate data acquisition and processing

The regional climate data was acquired remotely from the China Meteorological Data Network (http://data.cma.cn), the ECMWF Reanalysis 5th Generation (ERA5) (Hersbach et al. 2018), and the ERA5-Land (Muñoz-Sabater et al. 2021) databases for the survey period (2020/8/14–2020/9/24). Similar data collecting method is adopted widely by the studies in the field of remote sensing and geographic science (Xue et al. 2021; Yan et al. 2021; Liu et al. 2022). The feasibility of using the ERA5 reanalysis dataset as a proxy for onsite measurement was assessed by Krüger and di Napoli (2022) in southern Brazil based on the thermal index of the UTCI. The calculated thermal sensitivity and neutral UTCI from its regressions with mTSV, in-situ, and the ERA5 reanalysis data were quite similar.

Climate data such as dry bulb air temperature (T_a), relative humidity (RH) and wind speed at the height of 10 m (v_{10m}) were collected from the China Meteorological Data Network. These data were collected every hour. By adopting Eq. (1), the wind speed at 10 m height was converted to pedestrian-level height (1.1 m), which was also used in the well-known UTCI index to simplify wind speed at pedestrian level (Fiala et al. 2012). In this study, the regional climate data were collected based on the participant's location (the finest geographic unit is to a district) and time-of-point when they submitted the survey. Only the surveys filled in the outdoor condition were included in the follow analysis.

The radiation levels for participants in the outdoor environment were estimated by two conditions: shaded and unshaded. A sphere with angular factor of both 0.5 from the sky and land surface was used to simplify the mean radiant temperature (T_{mrt}) of participants in the unshaded area. The local short- and long-wave radiations received from the sky and land surface were collected from the ERA5 (Hersbach et al. 2018) and the ERA5-Land (Muñoz-Sabater et al. 2021) databases. Data was collected every hour.

Eqs. (2)–(8) were adopted for the calculation of T_{mrt}. More detail related to the calculation method of T_{mrt} and its reliability had been specified and discussed in the authors' previous publication (Liu et al. 2022).

Radiation data from the ERA5 and the ERA5-Land databases could not be used for participants in the shaded area because short-wave radiation was the primary influence on T_{mrt} and could be neglected for cases in the shaded area. As a field measurement conducted in Hong Kong with hot summer found that the difference between T_{mrt} and T_{a} was less than 3 °C (Xie et al. 2018). Thus, the mean radiant temperature T_{mrt} was assumed to be close to T_{a} for such cases. Such assumption was also applied in a study about a passive observation of pedestrian's choice of shaded and sunlit areas (Lai et al. 2017). Note that the assumption of $T_{\mathrm{mrt}} \approx T_{\mathrm{a}}$ allows a maximum error of 3 °C between the actual and approximate mean radiant temperature, leading to a PET difference of 0.8 °C.

The operative temperature (T_{op}) was defined as the weighted average of the mean radiant and air temperature following Eq. (9), as recommended by the ASHRAE Handbook (ASHRAE 2017). The radiative heat transfer coefficient (h_{r}) in Eq. (9) was calculated following Eq. (10), the recommend value of 4.71 W/(m²·K) in the ASHRAE 55 Standard was adopted here since it was sufficient for most conditions (ASHRAE 2020). The convective heat transfer coefficient (h_{c}) was calculated following the equation developed by de Dear et al. (1997) to cover the high wind speed conditions.

$$v_{1.1\mathrm{m}} = v_{10\mathrm{m}} \times \frac{\log(1.1/0.01)}{\log(10/0.01)} \tag{1}$$

$$I_{\mathrm{sw}} = \frac{f_{\mathrm{dir}}}{\cos\theta} / 3600 \tag{2}$$

$$D_{\mathrm{sw}} = (ssrd - f_{\mathrm{dir}}) / 3600 \tag{3}$$

$$R_{\mathrm{sw}} = (ssrd - ssr) / 3600 \tag{4}$$

$$D_{\mathrm{lw}} = strd / 3600 \tag{5}$$

$$U_{\mathrm{lw}} = (strd - str) / 3600 \tag{6}$$

$$f_{\mathrm{p}} = 0.308 \cdot \cos\left\{ \left(\frac{\pi}{2} - \theta\right) \cdot \left[1 - \frac{\left(90 - \frac{180}{\pi}\right)^2}{48402} \right] \right\} \tag{7}$$

$$T_{\mathrm{mrt}} = \sqrt[4]{\frac{1}{\sigma}\left[\left(\frac{\alpha_k}{\varepsilon_{\mathrm{p}}}\left(f_{\mathrm{p}} \cdot I_{\mathrm{sw}} + f_{\mathrm{a}} \cdot D_{\mathrm{sw}} + f_{\mathrm{a}} \cdot R_{\mathrm{sw}}\right) + f_{\mathrm{a}} \cdot \left(D_{\mathrm{lw}} + U_{\mathrm{lw}}\right)\right)\right]} - 273.15 \tag{8}$$

$$T_{\mathrm{op}} = \frac{h_{\mathrm{r}} T_{\mathrm{mrt}} + h_{\mathrm{c}} T_{\mathrm{a}}}{h_{\mathrm{r}} + h_{\mathrm{c}}} \tag{9}$$

$$h_{\mathrm{r}} = 4\varepsilon\sigma \frac{A_{\mathrm{r}}}{A_{\mathrm{D}}} \left(273.2 + \frac{T_{\mathrm{cl}} + T_{\mathrm{mrt}}}{2}\right)^3 \tag{10}$$

$$h_{\mathrm{c}} = 10.3 v_{1.1\mathrm{m}}{}^{0.6} \tag{11}$$

where,

α_{k}: the absorption coefficient for short-wave radiation (standard value: 0.7);

ε_{p}: the absorption coefficient for long-wave radiation (standard value: 0.97);

ε: the average emissivity of clothing or body surface (typically 0.95);

θ: the solar zenith angle of given location and date in radians;

σ: the Stefan-Boltzmann constant (5.67×10^{-8} W/(m²·K⁴));

A_{D}: the DuBois body surface area (m²);

A_{r}: the effective radiation area of the human body (m²);

D_{lw}: the upward long-wave radiation flux (W/m²);

D_{sw}: the isotropic diffuse short-wave radiation flux (W/m²);

f_{a}: the angular factor, 0.5;

f_{dir}: the direct solar radiation at 0.25° resolution (J/m²);

f_{p}: the projected area factor accounts for the directional dependence (dimensionless);

h_{c}: the convective heat transfer coefficient (W/(m²·K));

h_{r}: the radiative heat transfer coefficient (W/(m²·K));

I_{sw}: the anisotropic incident direct short-wave radiation flux (W/m²);

R_{sw}: the surface reflected short-wave radiation flux (W/m²);

strd: the surface thermal radiation downwards: the amount of thermal radiation emitted by the atmosphere and clouds that reaches the Earth's surface (J/m²);

ssr: the surface net solar radiation: the amount of solar radiation (both direct and diffuse) that reaches a horizontal plane at the surface minus the amount of reflected shortwave radiation from the surface (J/m²);

ssrd: the surface solar radiation downwards: the amount of solar radiation (both direct and diffuse) reaching a horizontal plane at the surface (J/m²);

str: the surface net thermal radiation: the difference between downward and upward thermal radiation passing through a horizontal plane of surface (J/m²);

T_{a}: the air temperature (°C);

T_{cl}: the average clothed body surface temperature (°C);

T_{mrt}: the mean radiant temperature (°C);

T_{op}: the operative temperature (°C);

U_{lw}: the downward long-wave radiation flux (W/m²);

$v_{1.1\mathrm{m}}$: the wind speed at the pedestrian-level height of 1.1 m (m/s);

$v_{10\mathrm{m}}$: the wind speed provided by the local weather bureau at the height of 10 m (m/s).

2.3 Calculation of thermal comfort index

PET was an equivalent temperature which was derived from the Munich Energy Balance Model for Individual (MEMI) (Höppe 1999). The RayMan-Pro software was used to calculate the PET values (Lee and Mayer 2016). The input parameters include participants' basic information (gender, age, height, weight, activity level, and clothing insulation), geographic location information of the city (latitude, longitude, and altitude), and regional climate data (T_a, RH, $v_{1.1m}$, T_{mrt}). Among the calculated parameters, T_a and RH were obtained from the China Meteorological Administration network, $v_{1.1m}$ was calculated from Eq. (1), and T_{mrt} was calculated from Eq. (2) to Eq. (8). Geographic location and basic information of participants were obtained from the survey. The metabolic rate and clothing insulation were calculated based on the ASHRAE 55-2020 (ASHRAE 2020) and the ISO-7730 (ISO 2005) Standards.

3 Results

3.1 Meteorological and demographic parameters

Table 2 provides general information about the local climate during the study, which includes T_a, T_{mrt}, $v_{1.1m}$, RH, and PET. Figure 1 presents distribution of T_a, T_{mrt}, $v_{1.1m}$ and RH during the survey. While T_a records large variations in maximum and minimum temperatures in Jiangsu, the data is generally warm-biased due to the study being conducted during late summer and early autumn. T_a is therefore 26.3 °C on average, with a standard deviation of 4.3 °C. A large variation is also recorded by T_{mrt}, with a maximum value of 92.3 °C, a minimum value of 18.1 °C, and the average value of 30.3 °C. During the survey period in Jiangsu, wind conditions are relatively low at pedestrian-level height, with the average $v_{1.1m}$ measuring only 1.0 m/s, which is described as "wind felt on face" in the Beaufort Scale (Forrester 1986). The RH ranges from 39.0% to 100%, with an average value of 85.4%, indicating a humid condition during the survey.

The distribution of survey samples and general information of participants are presented in Figure 2. In total, 1049 valid survey samples are collected from participants, and 1005 of them are filled out while wearing a face mask. Most of the survey samples (1018 out of 1049 valid samples) come from Yangzhou city of Jiangsu province. As of the purpose of this study, only the survey samples checked with the face mask option are considered for further analysis. All of the participants who wear a face mask reported wearing a disposable medical mask. 44.0% of the participants are male, while 56.0% of them are female during the survey (shown in Figure 2). A majority of participants are aged 36–50 and 51–75, which accounts for 29.6% and 45.1%, respectively.

A general overview of clothing insulation and metabolic rate can be found in Table 3. Clothing insulation presented here includes the clothing value of face mask, which is 0.1 clo

Table 2 General information about the local climate data during the survey

Parameter	Mean	Max	Min	Standard deviation
T_a (°C)	26.3	37.2	18.7	4.3
T_{mrt} (°C)	30.3	92.3	18.1	12.5
$v_{1.1m}$ (m/s)	1.0	3.3	0.3	0.5
RH (%)	85.4	100.0	39.0	16.3
PET (°C)	26.5	66.7	14.4	8.3

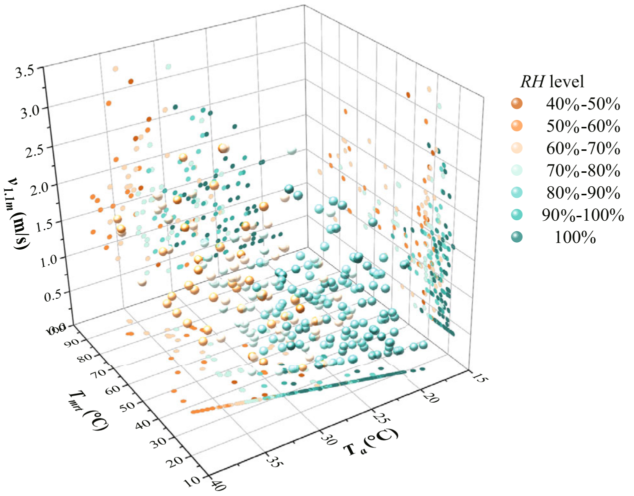


Fig. 1 The distribution of local climate data during the survey

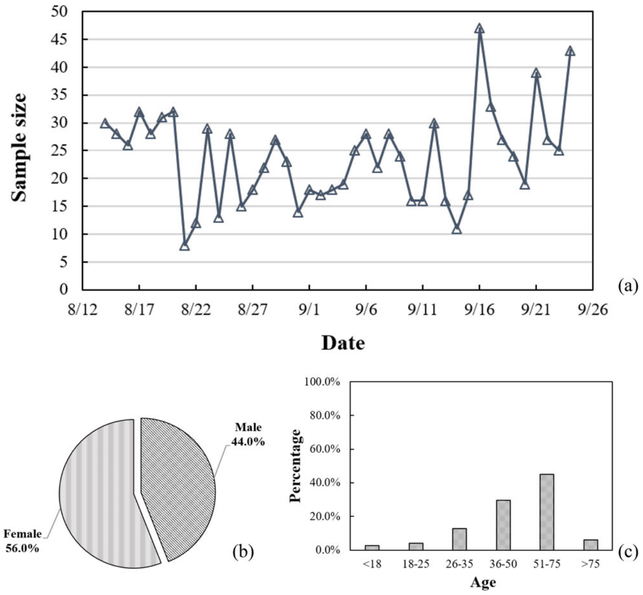


Fig. 2 The distribution of survey samples and general information of participants: (a) sample size distribution in each survey date; (b) gender distribution; (c) age distribution

Table 3 Clothing insulation and metabolic rate

	Mean	Max	Min	Standard deviation
Clothing insulation (clo)	0.55	1.01	0.32	0.15
Metabolic rate (met)	2.0	3.8	1.0	0.8

based on the measurement result of an experimental study of thermal manikin carried out by Zender-Świercz et al. (2021). During this study, most of the participants wore short-sleeved T-shirts and shorts, which resulted in the mean clothing value of 0.55 clo. The mean metabolic rate is 2.0 met, corresponding to the activity level of slow walking (at the speed of 0.9 m/s) according to the ASHRAE 55-2020 Standard (ASHRAE 2020).

Figure 3 shows the distribution of mask wearing duration before the participants completed the survey. Among the participants, 95.9% wear the face mask continuously for under 60 min, of which 80.7% wear it for 15–60 min. In the survey, only 4.1% of participants wear their face marks outdoors for more than an hour. Despite the availability of options for more than 2 hours, these are not checked. The survey data is consistent with the findings of an indoor study conducted by Tang et al. (2022), in which 75.0% of the respondents expected to wear masks for a period of less than two hours indoors.

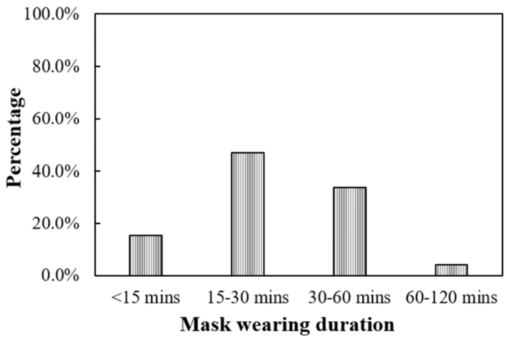


Fig. 3 Distribution of mask wearing durations

3.2 Subjective questionnaires results

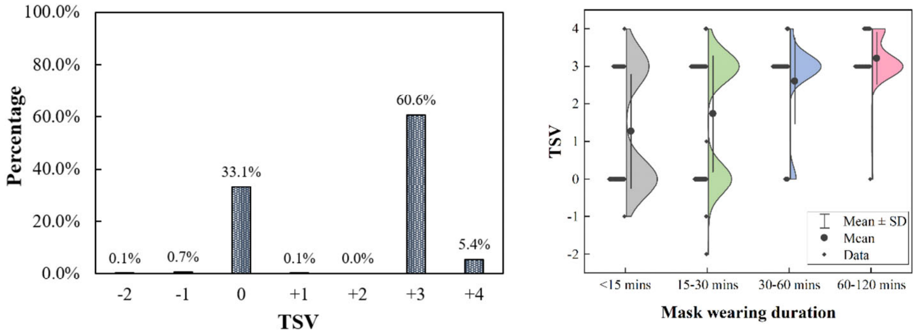
3.2.1 *The distribution of thermal sensation*

The distribution of TSV is presented in Figure 4(a). It is interesting that the voting of thermal sensation is polarized. The main votes consist of two sides: "neutral" (TSV = 0) and "hot" (TSV = +3), accounting for 33.1% and 60.6% of the total votes, respectively. Additionally, 5.4% of participants vote "very hot" (TSV = +4). Other options are rarely selected. The distribution of TSV is divided according to mask wearing duration for further information, and it is shown in Figure 4(b) by violin plot. Kernel smoothing is used to produce this violin plot. As the duration of mask wearing increases, the mean TSV increases as well. The mean TSV for those who wear face masks less than 15 min is simply 1.3, and it becomes 1.7 for those who wear face masks for 15–30 min. The mean TSVs are recorded as 2.6 and 3.2 when the mask wearing durations reach 30 min and 60 min. When the mask wearing duration reaches 30 min, the vote of "neutral" (TSV = 0) almost disappears and the thermal sensation concentrates at the side of "hot" to "very hot".

3.2.2 *Preference votes for meteorological parameters*

Figure 5(a) shows the percentage distribution of preference votes for meteorological parameters. Preference votes can generally reflect the needs of participants wearing masks in terms of thermal comfort. Since most participants' votes for thermal sensation emphasize warm sensations, it is reasonable that most would want T_a and T_{mrt} to be lowered, with 66.0% and 91.4% respectively. It appears that most participants would prefer a higher wind speed (62.3%), and would like the humidity to remain unchanged (65.4%) or higher (34.2%). In spite of the high humidity level during the survey period, participants remained in favor of higher relative humidity, only 0.4% said that they wanted it lower.

The distribution of preference votes for meteorological parameters is further investigated by dividing them into a



(a) (b)

Fig. 4 (a) The overall distribution of TSV; (b) the violin plot of the distribution of thermal sensation votes in different mask wearing durations

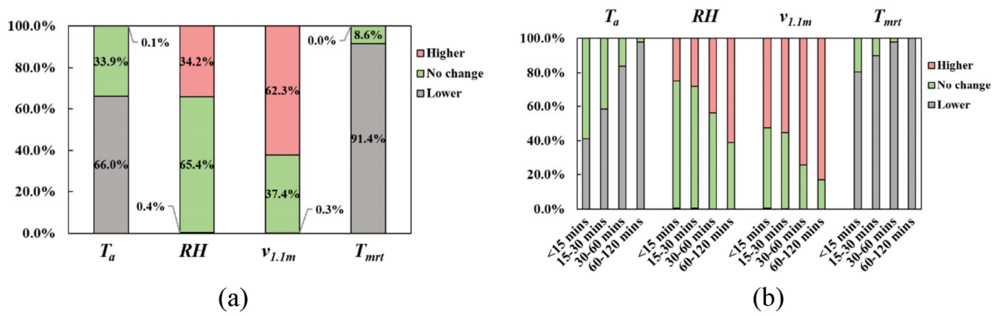


Fig. 5 (a) Percentage distributions of preference votes for meteorological parameters; (b) percentage distributions of preference votes for meteorological parameters in different mask wearing durations

variety of mask wearing durations (Figure 5(b)). There is no doubt that as the mask wear time increases, more participants wish to reduce T_a and T_{mrt}. When they wear face masks outdoors for 60–120 min, nearly all of them want to reduce the ambient temperature. By contrast, the percentages of wanting higher *RH* and $v_{1.1m}$ increase along with the duration of wearing the mask. For those who wear the face mask for 60–120 min, these percentages increase by 36.1% and 30.6% respectively, compared to those who wear the face mask for less than 15 min.

Figure 6 shows the differences in people's preferences for T_a under different mask wearing durations. Most participants expect lower T_a when it is higher than 28 °C regardless of mask wearing duration. Under different mask wearing durations, temperature preference varies mainly from 20.0 to 28.0 °C. Within the T_a range of 24.0 to 28.0 °C, the proportion of people wanting to lower T_a grows from around 50% for groups under 15 min to 100% for groups between 60 and 120 min. Moreover, apart from the group wearing a face mask for 60–120 min not having record of T_a from 20.0 to 24.0 °C, all the other groups show a clear increase in wanting lower T_a along with the increase in mask wearing duration even in the range of 20.0 to 24.0 °C, which is generally considered as a cool to neutral temperature range in traditional outdoor thermal studies for walking people (Labdaoui et al. 2021).

The distribution of participants' preference for *RH* is shown in Figure 7. There are very few participants who expect to lower *RH* in all *RH* ranges; it only accounts for less than 5% for ranges between 50% and 70% and disappears for other *RH* ranges. Most participants expect *RH* to remain unchanged or to increase. There is a fluctuation from the *RH* value of 40% to 70% in the percentage of respondents who wish for *RH* to remain unchanged or higher. However, with an increase in *RH* from 70%, the percentage of expecting unchanged *RH* increases.

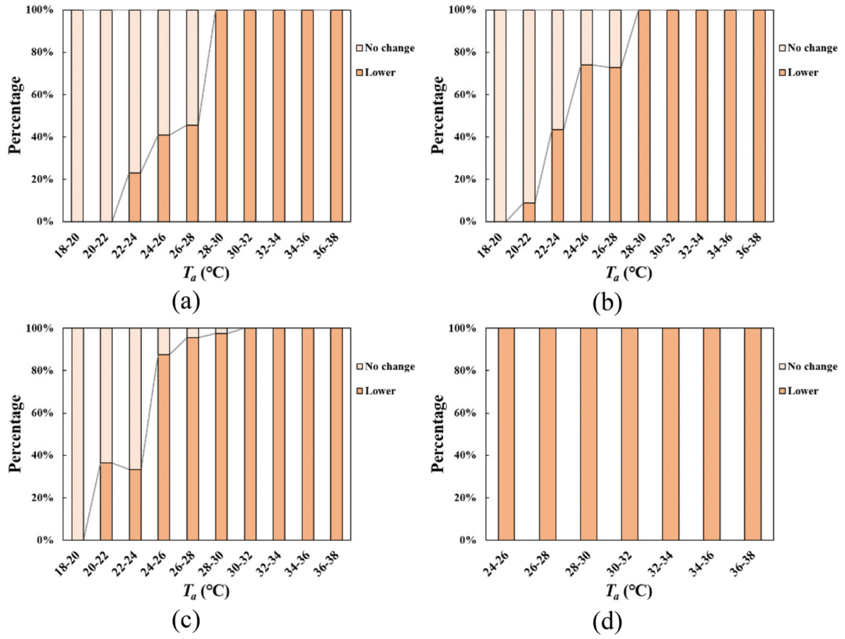


Fig. 6 The distribution of participants' preference for different T_a under the case of wearing mask for (a) less than 15 min; (b) 15–30 min; (c) 30–60 min; (d) 60–120 min

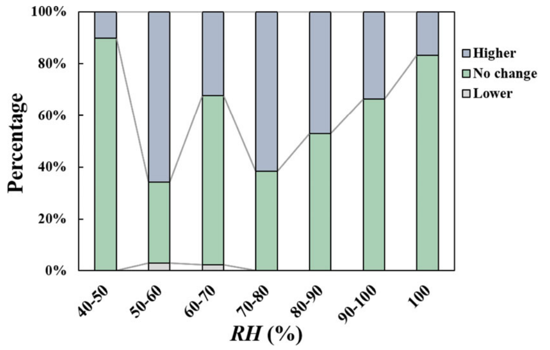


Fig. 7 The distribution of participants' preference for *RH*

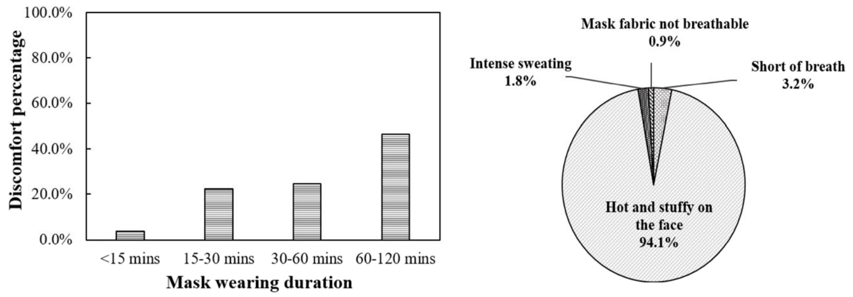
3.2.3 *Mask wearing and the causes of discomfort*

The online survey asks the question "Does wearing the mask make you feel uncomfortable?" and provides the reasons for it. Participants who answer "yes" to the first question must provide the corresponding reasons. The voting results are presented in Figure 8. Figure 8(a) shows the percentage of discomfort associated with different mask wearing durations, and Figure 8(b) shows the causes of discomfort. As the mask wearing duration increases, it is evident that the percentage of discomfort grows. Wearing a face mask for less than 15 min is associated with a percentage of discomfort of 3.9%, and for less than an hour, the percentage remains 23.0%. For people wearing a face mask for over an hour, the percentage reaches 46.3%. Among those who voted feeling discomfort, 94.1% of them attribute the discomfort feeling "hot and stuffy on the face".

3.3 The influencing factors of TSV

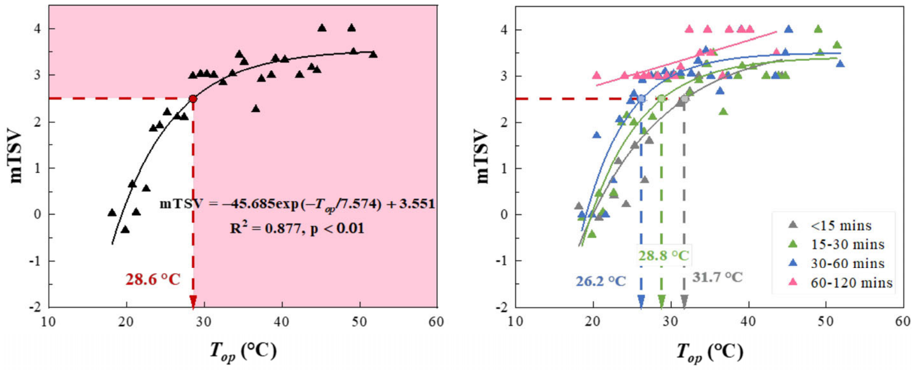
3.3.1 *The influence of mask wearing duration on TSV*

Figure 9 represents the relationship between mean thermal sensation vote (mTSV) and T_{op} using the exponential equation. Table 4 shows detail information of regressions of different mask wearing durations. Figure 9(a) shows the correlation between T_{op} and all mTSV data from all mask wearing durations. The correlation can be quantified well by an exponential equation, with R^2 = 0.877. Figure 9(b) shows the correlation between T_{op} and mTSV for each mask wearing duration. Expect for the mask wearing duration of 60–120 min, all other relationships can be quantified by exponential regression with high coefficients of determination ($R^2 > 0.70$) (shown in Figure 9(b)). The reason for low R^2 in 60–120 min group, however, is that the mTSV concentrates in the limited range of "hot" (TSV = 3) and "very hot" (TSV = 4), thus limiting the change of slope. When the T_{op}



(a) (b)

Fig. 8 Discomfort caused by mask wearing: (a) the percentage of discomfort caused by mask wearing in different durations; (b) the causes of discomfort



(a) (b)

Fig. 9 The relationship between mean mTSV and operative temperature in (a) all mask wearing durations; (b) different mask wearing durations

Table 4 Detail information of exponential regression for mTSV vs. T_{op}

Mask wearing duration (min)	Regression equations	R^2
0–15	mTSV = −23.807exp(−T_{op}/10.733) + 3.739	0.787
15–30	mTSV = −59.930exp(−T_{op}/6.890) + 3.420	0.875
30–60	mTSV = −96.390exp(−T_{op}/5.745) + 3.507	0.813
60–120	mTSV = −6.150exp(−T_{op}/84.354) + 7.592	0.416

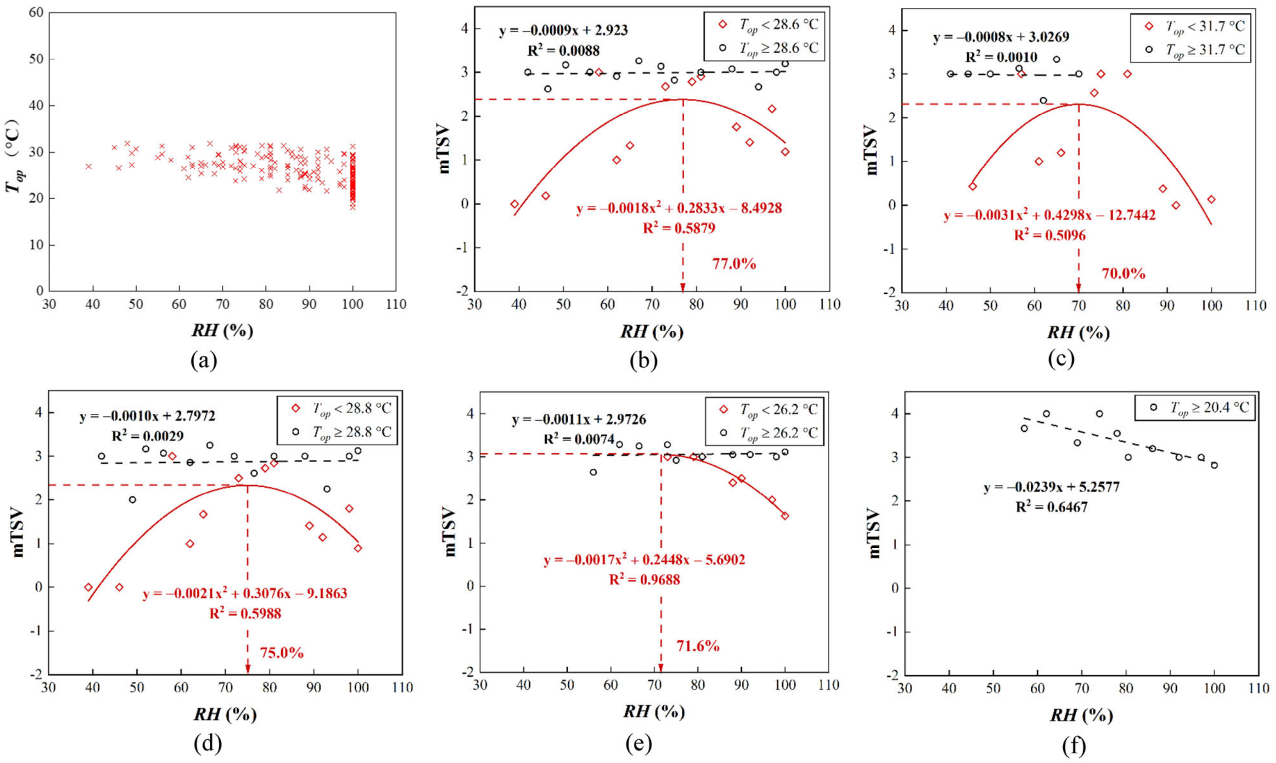
exceeds 28.6 °C, the majority of participants feel hot and very hot (TSV ≥ 3).

For mask wearing durations less than 60 min, it is noteworthy that for each regression line an elbow point exists. When T_{op} surpasses such a point, mTSV remains between "hot" and "very hot" regardless of increases in T_{op}. In this case, the elbow point as 0.5 scale of TSV less than "hot" (TSV = 3) is assigned. Based on assigning this elbow point a TSV of 2.5, for mask wearing periods of less than 15 min, 15–30 min, and 30–60 min, the corresponding T_{op} are calculated to be 31.7 °C, 28.8 °C, and 26.2 °C, respectively. In other words, by wearing a mask for a longer period of time in the warm-biased environment, the same thermal environment is perceived as hotter.

3.3.2 *The influence of RH on TSV*

A few previous studies have found that outdoor humidity and wind speed have less effect on human thermal perception than T_a and T_{mrt} (Chan and Chau 2019; Fang et al. 2021; Feng et al. 2021), but wearing a face mask blocks the expiratory current, which creates a specific microclimate on the lower part of the face with a higher humidity inside. As a result, it is desirable to investigate the influence of environmental relative humidity on thermal sensation for people wearing masks. Since the T_{op} is the weighted average of T_a and T_{mrt}, the influence of *RH* is not quantified in the T_{op} in the analysis of Section 3.3.1. Therefore, the method used in Section 3.3.1 is repeated here, and the calculated T_{op} corresponding to TSV = 2.5 as a dividing line is used for discussing *RH* separately.

The relationships among T_{op}, mTSV and *RH* for different mask wearing durations are shown in Figure 10. Figure 10(a) demonstrates the relationship between T_{op} and *RH* when the T_{op} values below 32 °C. T_{op} shows slight differences with ranging from 28 °C to 32 °C though the *RH* increasing from 40% to 100%. Meanwhile, Figure 10(b) shows data points from all mask wearing period, while Figures 10(c)–(f) shows the data of mask wearing duration of less than 15 min, 15–30 min, 30–60 min, and 60–120 min, respectively. Data with T_{op} corresponding to TSV ≤ 2.5 are shown in red dots and data with TSV > 2.5 are shown in black dots in Figures 10(b)–(f). Note that the mTSVs for the case of wearing masks for over 60 min are all higher than 2.5, only black dots are shown in Figure 10(f).



(a) (b) (c)

(d) (e) (f)

Fig. 10 The relation (a) between T_{op} and *RH* for the T_{op} below 32 °C, and between mTSV and *RH* in different T_{op} ranges in case of mask wearing duration of (b) 0–120 min; (c) less than 15 min; (d) 15–30 min; (e) 30–60 min; (f) 60–120 min

In the cases with T_{op} values higher than the calculated critical values in each mask wearing duration, the participants' thermal sensation ranges from "hot" to "very hot", and the mean thermal sensation is almost independent of *RH*. These findings can be derived from the small slope and low R^2 of linear regressions between mTSV and *RH* of the groups of all data, 15–30 min, and 30–60 min. The values of mTSV all change significantly when *RH* is increased in cases where T_{op} are below the calculated critical value. By combining the information in Figure 10(a) showing that T_{op} only experienced minor fluctuations when *RH* was changed from 40% to 100%, it is apparent that RH is an important influencing factor for mTSV when people wear face masks. A quadratic regression can fit the relationship between mTSV and RH, and as the mask wearing duration increases, the quadratic regression fits better, with R^2 increasing from 0.5096 to 0.9688 as the duration increases from less than 15 min to 30–60 min.

In groups of all data, less than 15 min, 15–30 min, and 30–60 min, the mTSV peaks correspond to *RH* ranges between 70% and 80%. Results of mTSV decreases when *RH* exceeds this range. This phenomenon may be explained by the fact that when participants wear face masks for a certain period, the microclimate formed within the mask has a significant effect on overall thermal perception. Upon reaching a certain level of *RH*, the high humidity ratio in the inspiratory air combines with the vapor from the expiratory current, which forms saturated droplets inside the mask. Due to respiration, the evaporation process of these droplets is accelerated by the higher temperature inside the mask and the enhanced air movement by respiratory activity. In this case, increase $v_{1.1m}$ in ambient environment facilitates evaporation, which explains the preference for increase $v_{1.1m}$ as mask wearing duration increases (Figure 5(b)). In this process, evaporated droplets remove heat from the lower part of the face, which makes participants feel cooler. To confirm this interesting explanation, further variable-control experiments in the climate chamber should be conducted.

3.4 Assessing outdoor thermal comfort by PET

PET is used here as a thermal comfort index to evaluate the thermal condition of mask-wearing participants. The relation between PET and mTSV for all data is presented in Figure 11. The relationship between PET and mTSV can be quantified by an exponential function with a high coefficient of determination (R^2 = 0.895). Therefore, the relationship between PET and mTSV is clearly not linear, and its slope decreases with increasing PET. Slope decreases in a "slow followed by fast" pattern, and the PET range for the same amount of mTSV follows a "narrow followed by wide" pattern as well. In Table 5, the PET ranges for different levels of thermal sensation are quantified. As TSV is not a continuous vote, the PET ranges of a certain thermal sensation category were calculated by taking the PET corresponding to the ±0.5 scale. As an example, the PET range for "slightly warm" was calculated by assigning PET to TSVs of 0.5 and 1.5. In Table 5, the PET ranges for different thermal sensation levels show that the PET ranges widen with increasing thermal sensation. Specifically, the PET range corresponds to "slightly warm" is limited, a difference of 3.4 °C only (ranges from 17.6 to 21.0 °C). It increases to 5.7 °C in the category of "warm" (ranges from 21.0 to 26.7 °C), and it reaches 62.6 °C in the category of "hot" (ranges from 26.7 to 89.3 °C). The wide PET range corresponding to "hot" is mainly due to the limitation of thermal sensation level.

Figure 12 shows the relationship between mTSV and PET for different mask wearing durations, and Table 6 shows the details of each regression model for each mask wearing duration. Except for the case of wearing a mask for 60–120 min, the R^2 of the regression models are all higher than 0.75. As the *p*-values of the regression models are less than 0.01, the regression models are all significant. A prolonged use of the face mask actually makes the participants feel hotter in a warm-biased environment. In particular, the corresponding PET when mask-wearing participants feel "hot" (TSV = 3) for less than 30 min is 34.4 °C. As mask wearing duration increases, this value decreases to

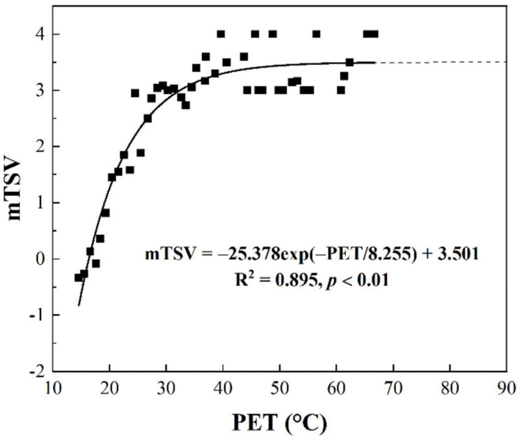


Fig. 11 The relation between PET and mTSV

Table 5 Thermal sensation categories while wearing face mask for 0–120 min

Thermal sensation	mTSV	PET range
Very hot	>3.5	>89.3 °C
Hot	2.5–3.5	27.6–89.3 °C
Warm	1.5–2.5	21.0–26.7 °C
Slightly warm	0.5–1.5	17.6–21.0 °C

28.4 °C for the duration of 30–60 min, and 24.7 °C for the duration over 60 min.

4 Discussion

4.1 A comparison with previous studies

A comparison of the data of with and without face masks is necessary to investigate the effect of face masks on thermal sensation. In light of the limited data in our study, a comparison with studies conducted in the same climate region is included. Here, reported studies with participants without face mask in humid subtropical regions with hot summers are summarized for comparison. Table 7 presents the regressions between mTSV and PET in this study and the other studies conducted in summer, and Figure 13 shows the comparison of the corresponding PET ranges in different TSV levels from the listed studies. PET values provide an objective description of the outdoor thermal environment; when the same thermal sensation corresponds to a lower PET range, the same thermal environment is perceived as hotter. Noted that the activity level of most of the listed studies are light activities such as sitting and standing, resulting in the mean metabolic rate ranging from 1.0 to 1.2 met. Only the research conducted in Guangzhou (Feng et al. 2021) has similar mean metabolic rate as our study. Their research focused on the thermal perception of the past 20-min thermal experience. Therefore, mask wearing durations of 0–15 min and 15–30 min are used to compare with their results. As shown in Figure 13, the PET ranges for the warm-biased thermal environment of the groups of 0–15 min and 15–30 min are lower than the results without mask wearing in the references.

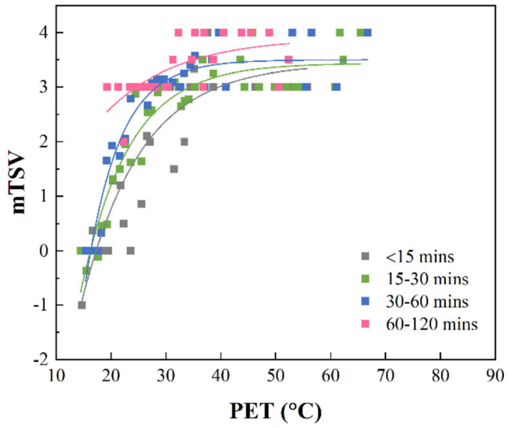


Fig. 12 The relation between PET and mTSV under different mask wearing durations

Table 6 Detail information of the regression models for PET and mTSV

Equation: mTSV = $A_1\exp(-\mathrm{PET}/t_1) + y_0$					
	A_1	t_1	y_0	R^2	p-value
<15 min	−17.047	10.797	3.435	0.756	<0.01
15–30 min	−21.950	8.760	3.435	0.881	<0.01
30–60 min	−49.253	6.170	3.497	0.886	<0.01
60–120 min	−5.916	13.135	3.906	0.406	<0.01

In the outdoor thermal comfort studies for low activity levels, linear regression is the well-suited model, regardless of the TSV scale used. This is confirmed by the high R^2 for each regression. It should be noted that the slope could be changed in a few specific conditions, for instance, this change has been found in Tang et al. (2021) with the focus of high activity levels. Specifically, they examined the thermal perception of construction workers every 30 minutes (Tang et al. 2021). Construction workers' activity levels are

Table 7 Regressions between mTSV and PET in this study and previous studies

Reference	Province/city	TSV scale	Mean metabolic rate (met)	Regression equation	R^2
This study (wear face mask for 0–15 minutes)	Jiangsu	9 points	2.0	$\mathrm{mTSV} = -17.047\exp(-\mathrm{PET}/10.797) + 3.435$	0.756
This study (wear face mask for 15–30 minutes)	Jiangsu	9 points	2.0	$\mathrm{mTSV} = -21.950\exp(-\mathrm{PET}/8.760) + 3.435$	0.881
Lian et al. (2020)	Shanghai	9 points	1.0–1.2	$\mathrm{mTSV} = 0.108\mathrm{PET} - 2.808$	0.904
Liu et al. (2016)	Changsha	9 points	Not provided	$\mathrm{mTSV} = 0.188\mathrm{PET} - 4.386$	0.778
Wei et al. (2022)	Chengdu	7 points	1.2	$\mathrm{mTSV} = 0.105\mathrm{PET} - 1.582$	0.834
Huang et al. (2019)	Mianyang	7 points	1.0–2.0	$\mathrm{mTSV} = 0.072\mathrm{PET} - 1.638$	0.868
Tang et al. (2021)	Guangzhou	9 points	2.0–4.0	$\mathrm{mTSV} = 0.122\mathrm{E}{-04}\mathrm{PET}^3 - 0.017\mathrm{PET}^2 + 0.797\mathrm{PET} - 9.273$	0.927
Feng et al. (2021)	Guangzhou	9 points	2.0	$\mathrm{mTSV} = 0.078\mathrm{PET} - 0.537$	0.630
Huang et al. (2017)	Hong Kong	7 points	1.2	$\mathrm{mTSV} = 0.129\mathrm{PET} - 3.233$	0.910
Cheng et al. (2012)	Hong Kong	7 points	1.0	$\mathrm{mTSV} = 0.137\mathrm{PET} - 3.434$	0.571

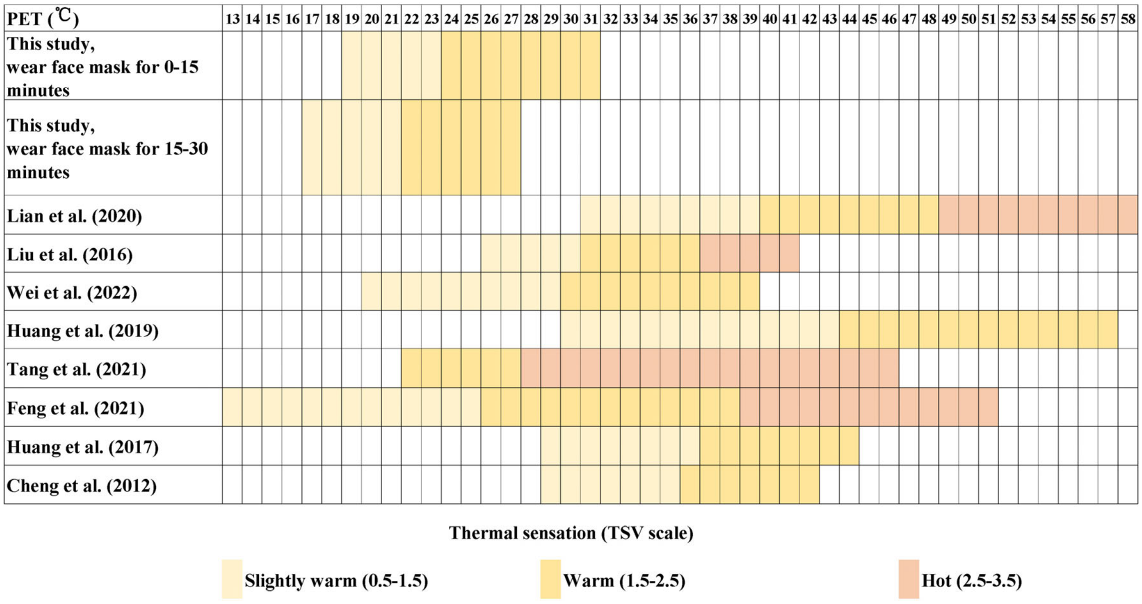


Fig. 13 A comparison of the PET ranges of various thermal sensation categories in this study and previous studies

estimated from 2.0 met (light machine work) to 4.0 met (pick and shovel work) based on the ASHRAE 55-2020 (ASHRAE 2020).

In both Tang et al. (2021) and the present study, the changing slope allows narrow variations in PET in the range of "slightly warm" to "warm", and wide variations in PET in the range of "hot". Hence, both the people who wear face masks (our study) and those with a high level of activity are highly sensitive to the change in temperature in warm-biased conditions. Furthermore, in Figure 13, the PET ranges of "warm" to "hot" in our study group with the face mask wearers for 15–30 min is similar to the results in Tang et al. (2021), suggesting that people who walk slowly with a face mask have similar thermal sensations as those who do not wear the mask but are in a much higher activity level. Such findings highlight the heat stress problems brought by mask wearing.

In light of the above discussion, it is clear that the effect of face masks on thermal sensation should not be simplified as a "normal clothing value" in the calculation of clothing insulation, not only because of the fact that it covers one of the thermal sensitive parts of our bodies, but also due to its influence on respiration.

4.2 Limitations of this study

The study is conducted through an online survey and remote data acquisition of meteorological parameters. It must be noted that this study has certain limitations. Firstly, the online survey does not allow the researchers to directly observe the participants' thermal history or mask wearing status. The answer of continuous time of wearing the mask is just a subjective judgement upon the memory of participants, which may result in possible errors in the analysis. Secondly, we must admit that we sacrifice certain microclimate parameter accuracy for wide spatial and temporal distributions of survey samples. Limited resources and manpower make it difficult to accomplish both missions. Therefore, the remote weather data from local weather bureau has been used to calculate the local thermal parameters of participants' thermal environment. It should be noted that local conditions such as the arrangement of buildings and trees may lead to different local meteorological parameters than calculated from the remote weather data. Though the authors have tried to make it up through classifying the datasets into sunlit and shaded conditions and adopted different methods quantifying their thermal conditions, bias still existed. According to Krüger and di Napoli (2022), the calculated UTCI values based on the ERA5 reanalysis data underestimate summer's UTCI by 3.8 °C, and overestimate winter's UTCI by 1.1 °C, but close to the in-situ values for transitional seasons. Based on their analysis, applying this method during summer may cause a bias, however, the mean bias and range of bias are limited. Even after taking into account these biases, the conclusions drawn from the present study are still valid. Thirdly, the results are only validated in summer, while data of other seasons may require further investigations. It is also valuable to further obtain the related T and RH data inside the face mask to better understand their influencing mechanism on the outdoor thermal comfort. Our next study will eliminate these limitations resulting from data acquisition methods, and subsequently more accurate results could be obtained to compare with the present study.

5 Conclusions

This study investigates the outdoor human thermal perception with considering the influences of face mask wearing duration and environmental relative humidity in the hot summer of eastern China by adopting online survey and the locally meteorological data. The findings are as follows.

(1) It appears that mask wearing participants prefer to lower both T_{a} and T_{mrt} in hot summers, while they expect RH and $v_{1.1\mathrm{m}}$ to rise or stay the same. For people who wear face masks, RH has an obvious impact on mTSV when mTSV is lower than 2.5. The mTSV first increases then decreases with the increase of RH values and peaks between 70% and 80%.

(2) The majority of participants wear the face masks for less than one hour outdoors. As mask wearing duration increases, the percentage of feeling uncomfortable increases dramatically, which is mainly attributed to the "hot and stuffy feeling in the face". Consequently, prolonged face mask usage significantly increases participants' thermal perception in warm-biased environments. Wearing a face mask for less than 30 minutes results in participants feeling hot in 34.4 °C PET, but over 60 minutes results in participants feeling hot in 24.7 °C PET.

(3) Based on the comparison of the present study and previous studies without mask wearing, it is concluded that wearing a face mask greatly impacts thermal perceptions. Those who wear face masks and walk slowly outdoors (2.0 met) have similar thermal responses to those who do an activity at a much higher metabolic rate (2.0–4.0 met) but wear no face masks.

In conclusion, the effect of face masks on thermal sensation in outdoor environments would not be simply calculated as it does as other clothing, and further variable-control experiments are necessary to quantify their thermal effects.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Ethical approval

The ethical approval by the university academic ethics office has been obtained before the study.

Author contribution statement

Rong Hu: Conceptualization, Investigation, Formal analysis, Writing—original draft. Jianlin Liu: Conceptualization, Methodology, Validation, Supervision, Writing—original draft, Writing—review & editing, Project administration, Funding acquisition. Yongxin Xie: Methodology, Software, Visualization, Writing—review & editing, Funding acquisition. Jiao Jiao: Investigation, Formal analysis, Validation. Zhaosong Fang: Conceptualization, Writing—review & editing. Borong Lin: Conceptualization, Writing—review & editing.

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Appendix A

Major questions in the online survey:

1. What is your current activity:

A. Sitting; B. Standing; C. Typing; D. Lying; E. Dinning; F. Jogging; G. Walking very slowly; H. Walking slowly; I. Walking quickly; J. Others.

2. What is your current location:

A. Outdoor shaded area; B. Outdoor sunlit area; C. Under the elevated building; D. Unclosed balcony; E. Closed balcony; F. Home (besides balcony). G. Office; H. Other indoor spaces.

3. Are you wearing a face mask properly at this time:

A. Yes; B. No.

4. What type of face mask are you wearing at this moment:

A. Plain cotton mask; B. Plain gauze mask; C. Disposable medical mask; D. Disposable surgical mask; E. N95 mask; F. KN95 mask; G. Others.

5. How long have you kept wearing the mask:

A. Less than 15 minutes; B. 15–30 minutes; C. 30–60 minutes; D. 1–2 hours; E. 2–3 hours; F. 3–4 hours; G. More than 4 hours.

6. What is your current thermal sensation level:

A. Very cold; B. Cold; C. Cool; D. Slightly cool; E. Neutral; F. Slightly warm; G. Warm; H. Hot; I. Very hot.

7. What is your current thermal comfort level:

A. Very uncomfortable; B. Uncomfortable; C. Neutral; D. Comfortable; E. Very comfortable.

8. Does wearing the mask make you feel uncomfortable:

A. Yes; B. No.

9. Where do you feel most uncomfortable after wearing a mask:

A. Head; B. Face; C. Back; D. Chest; E. Arm; F. Leg; H. Foot.

10. What is the cause of your discomfort after wearing a mask:

A. Short of breath; B. Hot and stuffy on the face; C. Intense sweating; D. Mask fabric not breathable; E. Bad mood; F. Others.

11. What are your expectations for the current environment:

Temperature: A. Lower; B. No change; C. Higher.
Humidity: A. Lower; B. No change; C. Higher.
Wind speed: A. Lower; B. No change; C. Higher.
Sunshine: A. Lower; B. No change; C. Higher.