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Experimental investigation of the effects of personal protective equipment on thermal comfort in hot environments

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ARTICLE INFO

Keywords:
COVID-19
Health care workers
Personal protective equipment
Transition space
Thermal comfort

ABSTRACT

Since the outbreak of COVID-19, wearing personal protective equipment (PPE) has become increasingly common, especially for healthcare workers performing nucleic acid sample collection. A field experiment and questionnaire survey were conducted in a semi-open transition space of a university building in Guangzhou, southern China. Thirty-two subjects wore PPE to simulate nucleic acid sample collection, during which thermal parameters were recorded and subjective questionnaires were completed. The relationship between thermal sensation and thermal index was analyzed to determine the neutral temperature and comfort temperature zones. Subjects had higher requirements for thermal environment parameters when wearing PPE than when not wearing PPE, and were found to have statistically significant differences in thermal perception when wearing and not wearing PPE. Wearing PPE significantly raised the subjects’ thermal and humidity sensations and restricted their airflow. Wearing PPE resulted in thermal discomfort for the subjects and a high unacceptability rate for environmental thermal parameters. The subjects wore PPE for an acceptable duration of approximately 1.5 h. The neutral operative temperatures were significantly lower when wearing PPE than when not wearing PPE, and the deviation from the neutral temperature was 9.7 °C. The neutral operative temperature was 19.5 °C and the comfort temperature zone was 17.4–21.5 °C when subjects wore PPE, demonstrating that subjects who wore PPE preferred lower temperatures. These results suggest that people who wear PPE for work, especially outdoors, should receive more attention to ensure thermal comfort and safety.

1. Introduction

In recent years, the term climate change has appeared frequently in popular vocabulary and has received increasing attention. It has been described as the greatest global health threat of the 21st century [1]. Climate change due to greenhouse gas emissions is expected increase the global average temperature by 1.5–4 °C by the end of the 21st century [2]. Compared with the pre-industrial period, climate change has led to a warming of 0.8–1 °C [3]. In addition, a relationship between increased temperature and increased mortality and morbidity has been found in several areas worldwide [4–7], indicating that humanity is vulnerable to exposure to hot ambient conditions and associated heat stress. Future climate projection studies [8–10] have shown that the rising temperature shift has already manifested in an increase in the frequency, intensity, and duration of heatwaves, resulting in a greater impact on public health.

On March 11, 2020, the World Health Organization (WHO) announced the COVID-19 outbreak as a pandemic. According to the World Meteorological Organization (WMO), 2019 was the second warmest year and the last five years were the warmest on record [11]. Many countries worldwide have managed to enact a series of specific measures to contain and counterbalance the transmission of SARS-CoV-2, including the use of various COVID-19-specific personal protective equipment (PPE-COVID-19) to perform several activities outside the home (both outdoors and indoors) [12]. Thus, the overlap between COVID-19 and heatwaves has become inevitable, and it is common for people to wear personal protective equipment (PPE), particularly health care workers (HCWs). PPE components include overalls, face masks, gloves, goggles, and shoe covers, the use of which is likely to cause significant physical and psychological stress to the
parameters were transformed an experiment in a climatic chamber (the microclimate). The metabolic rate during activity [22] indicates a problem with disposable protective clothing is a poor comfort level and increasing the risk of heat stress [15]. Because the wearer properties to prevent infection by external viruses [13]. Because the wearer. PPE, as the basic protective equipment for HCWs, has effective barrier properties to prevent infection by external viruses [13]. Because the high level of protection required by PPE severely hinders heat exchange owing to sweat evaporation [14], the state of HCWs when wearing PPE approximates a thermodynamically closed system with no molecular or very limited energy transfer between the wearer and the external environment, resulting in a significant reduction in their heat loss, severely affecting their productivity and health in hot weather, and increasing the risk of heat stress [15–18].

Some previous studies on PPE have been performed. A common problem with disposable protective clothing is a poor comfort level [19–21]. Several studies have reported the effects of protective clothing characteristics, notably the number of layers, weight, and fit, on metabolic rate during activity [22–25]. Zwolinska and Bogdan [26] performed an experiment in a climatic chamber (the microclimate parameters were ta = 24 °C, RH = 40%, Va = 0.1 m/s) to study the impact of medical clothing on the thermal stress of surgeons performing their work with a high metabolic rate. The results indicated that, during a surgical procedure, the surgeon’s body was subjected to thermal load. Some studies have focused on the impact of protective clothing design and material composition on human thermal comfort [27–29]. For example, Troynikov et al. [27] discussed the performance properties related to the thermal physiology and comfort of the wearer in relation to the function of protective clothing, along with comprehensive testing and analysis of the constituent materials and thermal manikin testing of experimental surgical clothing. Su et al. [28] proposed the use of a portable cooling device to improve the interior thermal and humid environment of protective clothing for medical use. Chong et al. [30] investigated the relationship between physiological responses and subjective perceptions of workers wearing thermal protective clothing in a hot environment and developed a continuous graphical index to assess heat strain in hot environments. Some studies [31–33] have reported physical symptoms and heat stress in health care workers while wearing PPE, along with impaired cognitive and physical performance and adverse health effects. Few studies have investigated the thermal comfort and responses of HCWs working outdoors in hot and humid environments, particularly when wearing PPE. However, since the pandemic was declared, HCWs often conduct nucleic acid sample collection outdoors, either under temporary tents or in a semi-open transition space. Nucleic acid collection medical personnel are indispensable in the fight against COVID-19 pandemic. Therefore, further research is needed on the thermal comfort and responses of HCWs wearing PPE during nucleic acid sample collection outdoors. In this study, a field experiment was conducted in a semi-open transition space of an academic building at Guangzhou University, aiming to investigate the thermal comfort and responses of health care workers wearing PPE while performing nucleic acid sample collection outdoors. The volunteers were invited to complete thermal comfort questionnaires, and the thermal ambient parameters were measured.

Thus, the results of this study improve our understanding of the impact and knowledge of HCWs wearing PPE while working outdoors in hot environments, including thermal, physiological, and psychological responses as well as health. This study provides a reference and support for reasonable thermal management and the development of cooling strategies for HCWs working in hot weather conditions, which is important for mitigating heat stress in HCWs and ensuring their thermal comfort and safety.

2. Methodology

This study was conducted by method of objective thermal environment parameter measurements and subjective questionnaires. In fact, we could not conduct subjective questionnaires on HCWS when they were operating because it would interfere with their work. Therefore, we conducted a field experiment inviting school students as volunteers to simulate the collection of nucleic acid samples while completing a subjective questionnaire. When we cannot complete experimental investigations in a real operating environment, inviting volunteers and simulating the operating environment is an alternative method. This method of restoring the operating environment allows experiments to be conducted, and its feasibility and applicability are certain and can be extended.

2.1. Meteorological conditions of the survey area

As shown in Fig. 1, Guangzhou (112 °E to 114.2 °E and 22.3 °N to 24.1 °N) is located in a hot summer and warm winter (HSWW) region,
and has a climate characterized by long hot summers with high humidity and warm winters. The monthly average temperatures were above 28 °C (the monthly average maximum temperature was higher than 33 °C) during July and August. During these months, the monthly mean values of relative humidity were close to 80%. These conditions often contribute to creating average thermal conditions during the summer months, characterized by moderate and strong heat stress. Our study was conducted in September 2021. Based on data from the Guangzhou Meteorological Station, the range of outdoor air temperature was found to vary between 24 °C and 37 °C, and the mean temperature reached 30.5 °C (Fig. 2). The daily average relative humidity ranged between 60% and 85% and the monthly average relative humidity was 71%. Therefore, even in September, Guangzhou was still very hot and humid.

2.2. Measured parameters and instruments

This study was conducted in the semi-open transition space of the Guangzhou University academic building in late September 2021. During the experimental period, the environmental thermal parameters, air temperature (T<sub>a</sub>), relative humidity (RH), globe temperature (T<sub>g</sub>), and air velocity (V<sub>a</sub>), were automatically recorded using a thermal comfort level recorder and an universal air velocity recorder. Detailed information on the instruments used in the experiments is provided in Table 1.

2.3. Subjects and subjective questionnaire

In this study, the GPower software, a noncommercial program for performing various types of power and statistics analysis, was used to determine the number of subjects. According to the guidelines in the study [34], the number of subjects in this experiment was determined to be 32. Due to the epidemic, the intercommunity was strictly closed and controlled, so it was difficult to invite other age groups as subjects. We recruit subjects through campus advertisements, which are circulated mainly among students. So the subjects in this experiment are mainly young college students. And, in one of our previous surveys, the proportion of nucleic acid sample collectors between the ages of 17 and 30 was approximately 33.7% (total of 2190). Therefore, there is a certain importance and necessity to conduct experiments with young groups and the subjects in this experiment were young people. The thirty-two healthy subjects, including 20 women and 12 men, were recruited through advertisements distributed on the university campus to participate in this experiment. All of them were college students at Guangzhou University, and had all lived in Guangzhou for more than a year. All subjects reported no history of disease (such as hypertension or

![Fig. 2. Outdoor thermal environment parameters in Guangzhou in September 2021.](image)

Table 1: Detailed information of instruments used in this study.

| Instrument Type       | Parameter | Measuring Range | Accuracy | Sampling Rate (s) |
|-----------------------|-----------|-----------------|----------|-------------------|
| Universal air velocity recorder | V<sub>a</sub> (m/s) | 0.05-5.00 m/s | 5% ± 0.05 m/s | 30 |
| Thermal comfort level recorder | T<sub>a</sub> (°C) | 20-+80 °C | ±0.3 °C | 30 |
|                       | RH (%)    | 0.01-99.9% | ±2% RH (10-99% RH) | 30 |
|                       | T<sub>g</sub> (°C) | 20-+80 °C | ±0.3 °C | 30 |

Table 2: Detailed subject information.

| Gender | Sample size | Age (y) | Height (m) | Weight (kg) | BMR (kcal/day) | BMI |
|--------|-------------|---------|------------|-------------|----------------|-----|
| Female | 20          | 20.8    | 1.60       | 51.5        | 1340.1         | 20.0|
| Male   | 12          | 23.4    | 1.71       | 61.5        | 1597.1         | 21.3|
| Average| –           | 22.1    | 1.66       | 56.5        | 1468.6         | 20.7|

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Table 3
Subjective vote scale.

| Thermal sensation | Humid sensation | Blowing feeling | Thermal preference | Humid preference | Blowing preference | Acceptability |
|--------------------|-----------------|-----------------|--------------------|-----------------|-------------------|---------------|
| +4 very hot        | +4 extremely humid | +4 very strong | +4 higher          | +4 higher       | +4 higher         | +4 acceptable |
| +3 hot             | +3 very humid    | +3 warm         | +3 neutral         | +3 neutral      | +3 neutral        | +3 no change  |
| +2 warm            | +2 humid         | +2 cool         | +2 lower           | +2 lower        | +2 lower          | +2 unacceptable|
| +1 slightly warm   | +1 slightly humid| +1 slightly weak| +1 lower           | +1 lower        | +1 lower          | +1 unacceptable|
| 0 neutral          | 0 neutral        | 0 cool          | 0 neutral          | 0 neutral       | 0 neutral         | 0 no change   |
| -1 slightly cool   | -1 slightly dry  | -1 cold         | -1 lower           | -1 lower        | -1 lower          | -1 unacceptable|
| -2 cool            | -2 dry           | -23 very dry    | -2 weak            | -2 weak         | -2 weak           | -2 unacceptable|
| -4 very cold       | -4 extremely dry | -4 higher       | -4 lower           | -4 lower        | -4 lower          | -4 unacceptable|

Fig. 3. The formal experimental schedule.

Fig. 4. The change of mean air temperature and mean relative humidity with time of the experiment site.

Table 4
Thermal environment parameters of the experiment site.

| Parameters                | Abbreviation (units) | Maximum   | Minimum   | Mean     | Standard deviation |
|---------------------------|----------------------|-----------|-----------|----------|--------------------|
| Air temperature           | $T_a$ (°C)           | 34.3      | 29.1      | 31.9     | 1.3                |
| Globe temperature         | $T_g$ (°C)           | 36.2      | 29.3      | 32.1     | 1.4                |
| Mean radiant temperature   | $T_{mrt}$ (°C)       | 37.5      | 29.3      | 32.1     | 1.6                |
| Operative temperature     | $T_{op}$ (°C)        | 35.1      | 29.3      | 32.0     | 1.4                |
| Relative humidity         | RH (%)               | 91.8      | 62.2      | 72.3     | 5.4                |
| Air velocity              | $V_a$ (m/s)          | 3.78      | 0.12      | 0.64     | 0.55               |
cardiovascular disease), were non-smokers, were not chronically ill, and
did not take any medication during the experimental period. For both
sexes, the average age and body mass index (BMI) were approximately
22.1 years and 20.7, respectively. The average basal metabolic rate
(BMR) was 1468.6 kcal. Their detailed profiles are presented in Table 2.

During the experiment, all subjects were required to complete sub-
jective questionnaires. The questionnaire used in this experiment was
divided into two parts. The first part investigates the thermal sensation
vote (TSV), humid sensation vote (HSV), and air movement sensation
vote (ASV) under two conditions: wearing and not wearing PPE. The
acceptability and preference of the thermal environment parameters
were also recorded. The scale of the subjective vote was in accordance
with the thermal environment observed in ASHRAE-55 and ISO 7730
[35, 36]. The seven-point thermal sensation scales ranges from −3 to +3,
which is commonly used and suitable in indoor environments or mod-
erate environments. However, in hot and humid outdoor environments,
the limitations of the seven-point sensation scales should be taken into
account and HCWs wearing PPE operate under hot and humid outdoor
conditions. Thus, the nine-point thermal and humidity sensation scales
was more suitable to evaluate the outdoor thermal environment. And
the thermal preference expresses an expectation that the thermal envi-
ronment parameters will be changed to meet the demand. This expec-
tation can be positive or negative, or it can remain constant. Therefore, a
three-point (1 to +1) thermal preference scales was used in this study.

Detailed information is provided in Table 3. The second part investigates
not only the symptoms and uncomfortable parts of the body but also the
acceptable duration of wearing the PPE. A list of ten possible symptoms,
namely facial sultry, chest tightness, dyspnea, profuse sweating, dizzi-
ness and weakness, skin itching, nausea, blurry vision, rapid heartbeat,
and general weakness was created during this study.

2.4. Experiment procedure

Prior to participation, the subjects provided voluntary and informed
consent and were informed about the nature of the study and the poten-
tial risks of exposure to work on a hot weather day. This study was
approved by the appropriate institutional review board.

First, 32 subjects were divided into eight groups of four each. Eight
experimental tests were conducted between September 23 and 29, 2021,
in the semi-open transition space of an academic building at Guangzhou
University, China. As shown in Fig. 3, the formal experimental schedule
for each experimental test. The experiment started at 8:00 a.m. or 2:00
p.m. and ended at 12:30 p.m. or 6:30 p.m., which lasted approximately

![Fig. 5. Distribution of discomfort body parts when subjects wore personal protective equipment (PPE).](image1)

![Fig. 6. Distribution of discomfort symptoms when subjects wore personal protective equipment (PPE).](image2)

![Fig. 7. Distribution of percent thermal preference for environmental parameters with or without personal protective equipment (PPE).](image3)
270 min and consisted of three phases: the phase 1 (before wearing PPE, 20 min), the phase 2 (wearing PPE, 220 min), and the phase 3 (without wearing PPE, 30 min). In a study by Huizenga et al. [37], the human core and head temperatures were equilibrated within 30 min. Some previous studies [38–40] also adopted 20–30 min as the duration of the preparation for subjects. Therefore, in this experiment, 20 and 30 min were adopted as the duration of the preparation and recovery for subjects, correspondingly. As many nucleic acid sample collection HCWs work 2–4 h shifts, thus, the duration of wearing PPE in this experiment was set to 220 min.

During phase 1, subjects remained sedentary and familiarized themselves with the details of wearing the PPE. During phase 2, the subjects wore PPE and performed simulated nucleic acid collection tasks. During phase 3, the subjects took off the PPE and rested for 30 min. Simultaneously, subjects spent approximately 3–5 min filling out the questionnaire. It should be noted that subjective questionnaires were filled at 20-min intervals during phases 1 and 2 and at 10 min intervals during phase 3. Environmental parameters were automatically recorded for the duration of the experiment.

2.5. Data processing

2.5.1. The calculation of operative temperature

Operative temperature (T_{op}), an index widely used in thermal comfort studies that considers the effects of air temperature, mean radiant temperature, and air velocity on human thermal comfort, was used in this study and calculated by the following equation presented in the ASHRAE standard 55 [35]:

\[
T_{op} = T_a \times A + (1-A) \times T_{mrt}
\]  

(1)

Where A is a coefficient that depends only \( V_a \), when \( V_a \leq 0.2 \) m/s, \( A = 0.5 \); when \( 0.2 \) m/s < \( V_a \leq 0.6 \) m/s, \( A = 0.6 \); when \( V_a > 0.6 \) m/s, \( A = 0.7 \). \( T_{mrt} \) is calculated by substituting \( T_{sr} \), \( T_g \) and \( V_a \) into the equation presented in ISO 7726 [41] as follows:

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

(2)

where \( T_g \) is the air temperature, \( T_g \) is the globe temperature, \( V_a \) is the air velocity, \( D \) is the globe thermometer diameter (=0.15 m in this study), and \( \varepsilon \) is the emissivity (= 0.95 for black globe). Actually, according to the guidelines of ISO 7726, the diameter of the globe, a diameter of 0.15 m, is generally recommended when using equation (2) to calculate the mean radiant temperature, and this type of globe thermometer (\( D = 0.15 \) m) is widely used to measure the globe temperature.

2.5.2. Data analysis

The data from the experiments were imported into excel, including the content of the questionnaires filled out by the subjects and the measured thermal environment parameters. Then the data were classified and sorted. In addition, linear regression was used to analyze the relationship between the environmental parameters and responses to the subjective questionnaire to determine the neutral temperature. All statistical analyses were performed using IBM SPSS Statistics 25 (IBM Inc., Armonk, NY, USA), and Origin 2021 (Origin Lab Corporation, Northampton, MA, USA), including the fitting of linear regression equations and the calculation of linear regression correlation index R² and the independent sample t-tests. When the significance level was less than or equal to 0.05, there was a statistically significant difference between the tested levels. The figures and charts were created using IBM SPSS Statistics 25 and Origin 2021.

3. Results

3.1. Thermal parameters

The ambient thermal parameters obtained during the experiment are
show in Fig. 4 and Table 4. As shown in Fig. 4, the mean air temperature ranged from 31.1°C to 32.5°C and increased with time. The mean relative humidity between 70.8% and 74.9%. And seen in Table 4, the air temperature ranges between 29.1°C and 34.3°C, the relative humidity varies between 69.2% and 91.8%, and the air velocity varies between 0.12 m/s and 3.78 m/s. The mean $T_a$, RH, and $V_a$ were 31.9°C, 72.3%, and 0.64 m/s, respectively, which were higher than the monthly mean air temperature (30.5°C) and relative humidity (71%), indicating that the experimental site was rather hot and humid.

### 3.2. The impact of wearing PPE on human comfort

A total of 512 valid questionnaires were collected, 384 of which were completed by the participants while wearing PPE. The participants complained of discomfort caused by wearing PPE. As shown in Fig. 5, the proportion of facial discomfort was the largest (89.3%), owing to the fact that the protective mask almost covered the face, thereby limiting heat exchange between the face and the environment. The proportions of the head was 71.6% and 33.4% for chest. The vote for various uncomfortable symptoms continued to increase with the increase in the
duration for which the PPE was worn. As shown in Fig. 6, the percentage of voting for facial sultry reached 92.4%, followed by profuse sweating (78.9%) and dyspnea (66.4%). Some subjects also experienced other symptoms such as chest tightness (29.4%), blurry vision (37.3%), and rapid heartbeat (16.6%) while wearing PPE.

3.3. The impact of wearing PPE on thermal preference and acceptance

During the experiment, the subjects' thermal preferences and acceptance of the thermal environment parameters were recorded, as shown in Fig. 7 and Fig. 8. In this study, “thermal preference” refers to the subject’s desire for what changes in the parameters of the thermal environment will occur. Take “temperature” for example, it means subjects prefer the current temperature to be cooler or warmer or keeping unchanged to make them be thermal comfort. In some previous related studies [42–46], the “thermal preference” expression is the same as that of this study. When wearing PPE, almost all subjects preferred a lower temperature (89.5%), lower relative humidity (80.4%), and higher air velocity (90.6%), compared to 33.1%, 12.6%, and 4.4% when not wearing PPE. The acceptance votes for the thermal parameters showed a similar variation to the thermal preference votes, as shown in Fig. 8. Almost all subjects reported that they could not tolerate the thermal parameters when they wore PPE. Based on the distribution of thermal preferences and acceptance votes, it can be inferred that nucleic acid collection in semi-open transition spaces by HCWs in hot weather may involve health risks and heat stress.

3.4. The distribution of subjective sensation evaluations

3.4.1. Distribution of overall and local thermal sensation vote (TSV)

Fig. 9 (a) and (b) show the distribution of the TSV (overall and local) in the different phases. As shown in Fig. 9 (a), the percentage of voting thermal neutral (0) was the largest (37.5%), and the percentage of voting hot (+3) and very hot (+4) was 25.1% before the subjects wore PPE. However, when the subjects wore PPE, none felt thermally neutral, and the percentage who felt hot and very hot increased to 60.6% and 19.7%, respectively. When subjects rested after taking off their PPE, the percentage feeling thermally neutral was the largest (62.1%), with less than 5% of subjects feeling hot or very hot. As shown in Fig. 9 (b), subjects had a mean thermal sensation vote (MTSV) of 1.4 before wearing PPE and 0.3 without the PPE. However, owing to the thermal resistance of the PPE and the encapsulated environment imposed on the body, it was difficult for the body to dissipate heat, and the MTSV increased to 3.0 when the subjects wore PPE. However, when subjects took off their PPE, the MTSV was lower than that before wearing PPE, indicating that they felt cooler after taking off the PPE. This is probably because the intense sweating experienced while wearing the PPE makes the skin wetter. Furthermore, when the PPE is removed, sweat evaporation becomes easier, thus increasing heat dissipation from the body.

Fig. 10 (a–e) shows the distribution of local TSV in different phases, including the face, head, chest, back and limbs. It can be seen that wearing PPE also affects human local thermal sensation which has a similar distribution pattern to that of the overall thermal sensation. The TSV distribution of the face and head was more similar to the overall TSV distribution than that of the chest, back, and limbs, with the total percentages of those who voted hot and very hot while wearing PPE being 83.1% and 76.9%, respectively, which indicated that the correlation between the thermal sensation of the face and head and the overall thermal sensation was much stronger. Generally, it was not difficult to find that, both overall and local, subjects had lower values of TSV when without wearing PPE compared to before wearing PPE. In the same state of not wearing PPE, they felt cooler without wearing PPE than before wearing PPE. The reasons for this different results are as follows: firstly, there was a local fan behind each subject during the
whole experiment. Secondly, the subjects all increased sweating while wearing PPE and their skin was wetter. Thirdly, when subjects entered phase 3 (without wearing PPE), they had higher skin wetness at phase 3 than at phase 1 (Before wearing PPE). As a result of the above, sweat evaporation becomes easier and subjects emit more heat to the environment during phase 3 than during phase 1, and they felt cooler.

3.4.2. Distribution of humid sensation vote (HSV)

According to the results, wearing PPE had a significant effect on the sensation of humidity in the subjects. When subjects did not wear PPE, the percentage of voting humid neutral was 57.5%/75.8% (before/wearing PPE) and 22.5%/19.1% (before/without wearing PPE) in total voting slightly wet (1) and wet (2). However, while wearing PPE,
the percentage of those who felt wet reached 72.3%, with 10.9% of feeling extremely wet. As seen in Fig. 11 (b), subjects had a mean humid local thermal sensation vote, wearing PPE had a greater impact on and not wearing PPE. From the comparison of the mean difference of the sensation vote (including overall and local sensation) when wearing indicating that there was a statistically significant difference between wearing PPE, and no major differences were observed. However, while wearing PPE, the MHSV was significantly elevated and stabilized at 1.5, indicating that the environment between PPE and the body made them more susceptible to humidity.

3.4.3. Distribution of air movement sensation vote (ASV)

Fig. 12 (a and b) shows the distribution of the ASV in different phases. The results showed that wearing PPE had a significant impact on the sensation of air movement in the subjects. When the subjects did not wear PPE, the percentage of voting neutral was 47.5%/69.5% (before/without wearing PPE) and 40.1%/21.0% (before/without wearing PPE) in total, voting slightly strong (1) and strong (2). When subjects wore PPE, the percentage of votes that were slightly weak (−1), weak (−2), and very weak (−3) was 93.8%. As shown in Fig. 12 (b), the MASV (mean air movement sensation vote) of the subjects before and without wearing PPE was 0.4 and 0.2, respectively. However, while wearing PPE, their MASV was significantly decreased and stabilized at −2.2, indicating that they could barely feel air movement.

To explore the influence of wearing PPE on the human sensation vote and physiological parameters, independent sample t-tests were conducted using the SPSS software. The results are presented in Table 5 (a-b). From the t-test result, the p-value was smaller than 0.05 (p = 0.000), indicating that there was a statistically significant difference between the sensation vote (including overall and local sensation) when wearing and not wearing PPE. From the comparison of the mean difference of the local thermal sensation vote, wearing PPE had a greater impact on thermal sensation on the face and head than on the chest, back, and limbs.

3.5. The variations of acceptable duration

Fig. 13 shows the change in the acceptable duration of the subjects wearing PPE over time. It can be seen that the acceptable duration of the subjects was higher when they were not wearing PPE. When subjects wore PPE, the average acceptable duration decreased significantly during the first 20 min and then gradually increased to a stable level until the end of the experiment. Before wearing PPE, the acceptable duration ranged from 0 to 4.0 h, with an average value of 1.8 ± 0.9 h. When the subject wore PPE, the acceptable duration ranged between 0 and 3.5 h, with an average value of 1.4 ± 0.8 h. Without wearing PPE, the acceptable duration ranged from 0 to 4.0 h, with an average value of 1.6 ± 1.0 h. The results indicate that the experience of wearing PPE has a negative impact on the acceptability of subjects wearing PPE.

3.6. Correlation analysis of MTSV and operative temperature

The MTSV was calculated within 0.5 °C or 1.0 °C intervals of the T_{op}. Then, a linear regression between MTSV and T_{op} was conducted to predict the neutral T_{op}. The results are shown in Fig. 14 (a-e), and the regression equations are summarized in Table 6. The results from the linear regression revealed that subjects had lower MTSV when they were without wearing PPE than before wearing PPE. This is consistent with the results of the TSV distribution. The reason for this result has been explained above in 3.3.1. In general, wearing PPE resulted in subjects demanding a lower neutral temperature, and without wearing PPE, the neutral temperature of subjects was higher than that before wearing PPE. According to the linear regression equation, when MTSV = 0, the comfort temperature was calculated. Taking the overall MTSV as an example, the neutral temperature of subjects before wearing PPE was 29.2 °C. However, the neutral temperature was 19.5 °C when subjects were before wearing PPE. When subjects were before wearing PPE, the comfort operative temperature zone was 28.3–30.1 °C. However, the comfort temperature zone was 17.4–21.5 °C when they wore PPE. The results indicated that they required a much lower ambient temperature. More detailed information is presented in Table 6.

The differences in the MTSV corresponding to the T_{op} are shown in Fig. 15 (a-c), and the regression equations are summarized in Table 7. Strong linear correlations (R^2 > 0.7) were observed between ΔMTSV and T_{op}. For the overall MTSV, the results showed that the increment of MTSV due to wearing PPE presented a negative correlation with T_{op}, indicating a decrease in the overall TSV with increasing temperature. As for the local MTSV, compared with that before wearing PPE, the ΔMTSV
increased with $T_{op}$ in the head, chest, back, and limbs, except for the face. Compared with without PPE, $\Delta$MTSV increased with $T_{op}$ in the face, head, chest, and limbs, except for the back. The results indicate that due to wearing PPE, an enlarging increase in local TSV with increasing temperature but a lessening increase in overall TSV with increasing temperature.

4. Discussion

4.1. Impact of wearing PPE on human thermal comfort

Thermal sensation and comfort are important in occupational settings. According to a study by Fanger [47], the most important variables that influence the condition of thermal comfort are activity (M), thermal resistance of clothing, air temperature, mean radiant temperature, air velocity, and relative humidity. The variables were later quantified using a heat-balance equation and applied to thermal comfort [48,49].

In this study, we found that wearing PPE has a significant impact on human thermal comfort. There was a statistically significant difference in thermal comfort when HCWs wore and did not wear PPE in outdoor environments (e.g., when collecting nucleic acid samples in an outdoor semi-open transition space in hot weather). The high thermal resistance of PPE subjects wearers to a hotter environment, and the human body

![Fig. 14. Relationship between MTSV and $T_{op}$: (a) Overall, (b) face, (c) head, (d) chest, (e) back and (f) limbs.](image-url)
Building and Environment 222 (2022) 109352

Table 6

| Body part | Phase | Equation \( y = -0.0966x - 0.9966 \) | \( R^2 \) | Predicted neutral temperature (°C) |
|-----------|-------|-------------------------------------|--------|-----------------------------------|
| Overall   | Before wearing PPE | 0.6445 | 10.8 |
|           | Wearing PPE | 0.2848 | 18.6 |
|           | Without wearing PPE | 0.5169 | 27.3 |
| Face      | Before wearing PPE | 0.4124 | 25.6 |
|           | Wearing PPE | 0.7248 | 15.9 |
|           | Without wearing PPE | 0.6884 | 28.6 |
| Head      | Before wearing PPE | 0.5957 | 21.4 |
|           | Wearing PPE | 0.6907 | 17.0 |
|           | Without wearing PPE | 0.7554 | 30.5 |
| Chest     | Before wearing PPE | 0.8572 | 25.4 |
|           | Wearing PPE | 0.8293 | 30.9 |
|           | Without wearing PPE | 0.8293 | 30.9 |
| Limbs     | Before wearing PPE | 0.8379 | 24.9 |
|           | Wearing PPE | 0.8438 | 22.5 |
|           | Without wearing PPE | 0.9385 | 30.3 |

Table 6 Results of linear regression between MTSV and \( T_{op} \) in different phases.

Y. Mao et al.

responds to heat stress in two primary ways: vasodilation and secreting sweat onto the skin, resulting in increased cardiac load and therefore a faster heart rate and increased metabolic rate [50]. Furthermore, the encapsulated environment significantly impaired the radiant, convective, and evaporative heat exchange, and for most tasks, the external mechanical work rate was close to zero. Thus, wearing PPE increases heat storage in the body, resulting in thermal discomfort in hot weather conditions. As a result of wearing PPE, in this study, the subjects’ MTSV increased from 0.6 to 3.0, MHSV increased from 0.2 to 1.5, and MASV decreased from 0.3 to 0.2, resulting in a highly unacceptable rate of thermal environment parameters, including \( T_{op} \), RH, and \( V_s \). Furthermore, we found that the thermal response was more intense in the face and head than in other body parts when the participants wore PPE. The facemask, which covered almost the entire facial area and was in direct contact with the face and head, impeded heat dissipation through convective and respiratory exchanges as well as breathing, which explains the large proportion of face, head, and chest discomfort.

Subjects wearing PPE also demanded a much lower neutral temperature and comfort temperature zone. When the subjects were before wearing PPE, the neutral operative temperature was 29.2 °C and the comfort operative temperature zone was 28.3–30.1 °C. However, the neutral operative temperature was 19.5 °C and the comfort operative temperature zone was 17.4–21.5 °C when they wore PPE. In general, people wearing PPE need a more comfortable environment to reduce the thermal discomfort caused by PPE. Thus, there is a need to improve the thermal comfort of people wearing PPE. On the one hand, special PPE with ventilation and cooling can be customized for healthcare workers. Some studies [28,51–54] have tried to install fans on the PPE for cooling and ventilation to alleviate thermal discomfort. On the other hand, cooling vest with phase change materials (PCMs) or ice can be included underneath the PPE. The cooling vest absorb heat heat with a high storage density when the material changes from solid to liquid, taking away more heat from people and improving the thermal comfort. The use of cooling vest to reduce heat strain or improve thermal comfort in hot environments is indeed an effective adaptation measure [55–57]. Third, the ingestion of ice slurry is a popular strategy to mitigate heat strain in occupational and sports settings. Previous studies [58,59] have reported that ingestion of ice slurry is shown to reduce core body temperature prior to and during activity. Thus, ingestion of ice slurry prior to and during wearing PPE should mitigate the thermal discomfort. Forth, hand or upper-limb cooling in running water or a bucket of ice water during recovery breaks can also provide a meaningful cooling effect.

4.2. Impact of wearing PPE on human health

Owing to climate change, frequent and prolonged hot weather is expected to have catastrophic consequences on urban human settlements. Some previous studies [60–63] have indicated that heatwave disasters are related to the health of urban residents. Hot weather increases the risk of heat-related health problems such as elevated heart rate and body temperature, high blood pressure (BP), skin cancer, and allergic diseases [63]. Sometimes, high temperatures can lead to serious health problems, including respiratory problems, cardiovascular disease, and even death [60,64], and a significantly increased risk of cardiovascular hospitalizations in relation to heat exposure has been found [65]. The International Labour Organization estimates that more than 1 billion workers are exposed to high heat episodes, not all of which occur during the summer months [50]. There are reports that for occupational workers, extreme heat can cause negative effects, such as fatigue, decreased athletic performance, distractions, serious health hazards, and a decrease in productivity [66]. An overlap between heat waves and the COVID-19 outbreak unfortunately occurred during this pandemic. This field experiment was conducted at the end of September 2021 in Guangzhou, a typical subtropical city in China. As indicated in Fig. 2, even in September, the weather situation contributes to creating thermal conditions characterized by moderate and strong heat stress. Wearing PPE causes physical and psychological stress to wearers. On the one hand, as shown in Figs. 5 and 6, people experienced discomfort in body parts (face, head, chest, back, and limbs) because of wearing PPE, more commonly in the face and head. Simultaneously, people also experienced at least one physical symptom, as shown in Fig. 6, such as facial sultry, profound sweating, and dyspnea. Based on the findings of previous studies [67–69], breathing discomfort due to face masks has also been reported, which confirmed our finding that dyspnea due to wearing PPE is common among HCWs. Heavy sweating is a risk factor for human health [70]. Extended sweating depletes the plasma volume and osmotically important electrolytes. Thus, a slowly decreasing blood volume may compromise the mean arterial pressure. If systemic pressure can no longer be regulated, uncompensable hypotension will ensue [71]. Thus, based on related research [72,73], heat exhaustion in workers wearing protective clothing in hot-humid conditions (e.g., a subtropical climate) is more likely to be of cardiovascular origin (e.g., cardiovascular insufficiency) and is associated with uncompensable hypotension.

Furthermore, as shown in Fig. 13, The mean acceptable duration for the subjects was 1.8 h before wearing PPE and 1.6 h without wearing PPE. However, when the subjects wore PPE, the mean acceptable duration decreased to 1.4 h and the subjects reported being reluctant to wear PPE again in such hot weather and complained about the 4-h duration of wearing PPE. The changing trend during acceptable hours demonstrates the resistance of people to wearing PPE. Heat stress and the physical symptoms associated with wearing PPE can also cause a great deal of psychological stress. If the actual duration of wearing PPE is longer than what they can endure, it certainly increases the potential risk to their health. The prolonged duration of PPE usage is associated
with headaches as well as an important risk factor among healthcare workers, which was confirmed in a previous study \[31, 74–77\]. In addition, the longer the time that PPE is worn, the people the person will sweat. Heavy sweating stimulates the skin, causing redness, itching, and pain \[70\]. Therefore, developing effective adaptation measures to reduce the risk to HCWs’ health while taking anti-COVID-19 measures is necessary.

4.3. Limitations and future work

This study focused on investigating the thermal comfort and physiological responses of HCWs wearing PPE while performing nucleic acid sample collection in an outdoor semi-open transition space. This study had several limitations. Sometimes, nucleic acid sample collection is also carried out indoors or outdoors under awnings and therefore, more research should also be performed. PPE is used in different scenarios and seasons, such as transferring and handling patients in the receiving room and operating room. More studies related to wearing PPE in other scenarios and seasons should be conducted in future work. Since the subjects in this study were young college students, the effects of age need to be expanded for analysis in future studies. Meanwhile, gender differences in thermal and physiological responses while wearing PPE should be analyzed in the future. The microenvironment between the protective clothing and the human body, including the mask and face and the body torso and overalls, should be studied in greater depth in the future. Additionally, the site where this field experiment was done, Guangzhou in southern China, is located in a subtropical monsoon climate region with hot summers and warm winters. More research should be conducted in the future on the thermal comfort and response of HCWs wearing PPE while working outdoors in different other climatic regions. In fact, the data from this study have a certain reference and applicability in other regions with similar latitudes to Guangzhou, such as India and Pakistan, Iran and Mexico, Taiwan, and even Singapore.

5. Conclusions

Based on a field experiment and questionnaire survey, the thermal comfort and physiological indices of subjects wearing and not wearing PPE while performing nucleic acid sample collection outdoors were investigated, and thermal parameters were recorded. By analyzing the thermal sensations and physiological indices of the subjects in different
states, the following conclusions were obtained:

(1) The subjects experienced significant physical and thermal discomfort while wearing PPE, particularly on the face and head. Nearly 90% reported facial discomfort and over 70% reported head discomfort as a result of wearing PPE. The subjects also experienced a variety of physical symptoms, with facial slurry (92.4%) and profuse sweating (79.9%) being the main ones, along with dyspnea (66.4%) and chest tightness (29.4%).

(2) There was a statistically significant difference between thermal comfort when wearing and not wearing PPE. When the subjects wore PPE, the percentage that voted for hot and very hot, especially on the face and head, exceeded 80% for TSV, 70% for HSV, and 90% for ASV, where the airflow was barely felt. When they wore PPE, the MTSV, MHSV, and MASV were 3.0, 1.5, and −2.2, respectively; thus, they desired a lower temperature, relative humidity, and a stronger airflow.

(3) This study found that the experience of wearing PPE had a negative impact on the acceptance of subjects wearing PPE. Subjects wearing PPE showed a decrease in the acceptable duration of wearing PPE. With and without PPE, the average acceptable duration was 1.4 and 1.7 h, correspondingly. Taking into account heat stress, physiological responses and psychological stress, the recommended duration of wearing PPE is 1.5 h.

(4) In general, wearing PPE resulted in subjects demanding much lower neutral temperature and comfortable temperature zone. Based on the linear regression analysis, the neutral operative temperature before wearing PPE was 29.2 °C, while the neutral temperature while wearing PPE was 19.5 °C, i.e. a temperature difference of 9.7 °C, and the comfort temperature zone where subjects before wearing PPE was 28.3–30.1 °C and 17.4–21.5 °C when wearing PPE. In summary, the subjects who wore PPE required a colder thermal environment.

When people wear PPE, the customized PPE with ventilation and cooling and the use of cooling vest with PCMs can mitigate heat stress, physical symptoms and improve thermal comfort. Additionally, pre-cooling, precooling and post cooling can apply for those who wear PPE, such as the ingestion of ice slurry and the local parts of body cooling in ice water. A 1.5-h shift should be developed based on the subject’s acceptable duration of wearing PPE. And when wearing PPE to work indoors, it is recommended to keep the room temperature around 20 °C.

CRediT authorship contribution statement

Yudong Mao: Writing – original draft, Methodology, Data curation. Yongcheng Zhu: Methodology, Data curation. Zhisheng Guo: Methodology. Zhimin Zheng: Visualization, Methodology. Zhaosong Fang: Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. Xiaohui Chen: Visualization, Resources. Yudong Mao and Yongcheng Zhu contributed equally to this work.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Project No. 51978180), Guang Dong Basic and Applied Basic Reuter Foundation (2021A1515011671), the Key Medical Disciplines and Specialties Program of Guangzhou (2021–2023), and the Major Project of Guangzhou Health Science and Technology (grant number 2020AO31005). The authors express gratitude to all the subjects who participated in the survey.

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