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Human thermal physiological response of wearing personal protective equipment: An educational building semi-open space experimental investigation

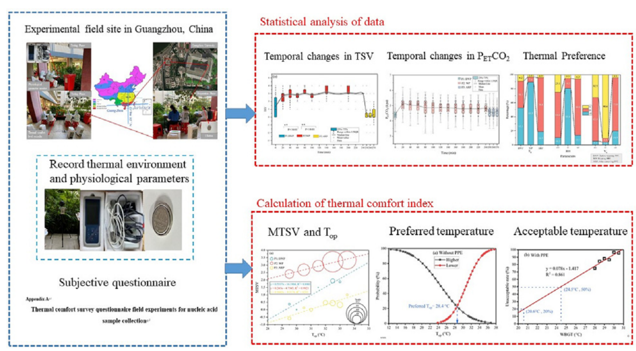
Zhaosong Fang [a], Yudong Mao [a], Yongcheng Zhu [b], Jiaxin Lu [a], Zhimin Zheng [a,*], Xiaohui Chen [b,*]

[a] School of Civil Engineering, Guangzhou University, Guangzhou, China
[b] The Second Affiliated Hospital of Guangzhou Medical University, Guangzhou, China

HIGHLIGHTS

- Differences in the physiological parameters with and without PPE were significant.
- Stronger airflow can mitigate thermal stress for subjects with PPE.
- Controlling and managing the duration of PPE use is essential to keep their health.
- Subjects with PPE required cooler thermal environment than that of without PPE

GRAPHICAL ABSTRACT



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ABSTRACT

With the outbreak and spread of the COVID-19 epidemic, HCWs are frequently required to wear personal protective equipment (PPE) for nucleic acid sample collection in semi-open transition spaces. Wearing PPE causes significant psychological and physical stress in HCWs. In this study, operative temperature (T_{op}) and wet-bulb globe temperature (WBGT) were used to assess thermal conditions through field experiments, while multiple physiological parameters were measured in the subjects. The results indicated that the subjects showed statistically significant differences in thermal perception and physiological parameters with and without PPE. Using observed increases in heart rate (HR), auditory canal temperature (T_{ac}), mean skin temperature (MST), and end-tidal CO_2 pressure, subjects were shown to have an increased metabolic rate and heat storage while wearing PPE. Additionally, a decrease in oxygen concentration was also observed, and this decrease may be linked to fatigue and cognitive impairment. Moreover, HR, MST, and T_{ac} showed a significant linear relationship, which increased with temperature and operative temperature, and the HR response was stronger with PPE than without PPE. The neutral, preferred, and acceptable temperatures were significantly lower with PPE than without PPE, and the deviations for neutral $T_{op}/WBGT$ were 9.5/7.1 °C and preferred $T_{op}/WBGT$ was 2.2/4.0 °C, respectively. Moreover, the upper limits of acceptable WBGT, 29.4 °C with PPE and 20.4 °C without PPE, differed significantly between the two phases. Furthermore, the recorded physiological parameter responses and thermal perception responses of the subjects while wearing PPE indicated that they were at risk of thermal stress. Overall, these results suggest that people who wear PPE should focus on their health and thermal stress. This study provides a reference for the development of strategies to counteract heat stress and improve thermal comfort.

* Corresponding authors at: The Second Affiliated Hospital of Guangzhou Medical University, Guangzhou, China.
E-mail addresses: zzmyyp@gzhu.edu.cn (Z. Zheng), cxhgz168paper@163.com (X. Chen).

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1. Introduction

By the end of the 21st century, it is anticipated that greenhouse gas emissions will result in the world's mean temperature increasing by 1.5 to 4 °C (Wehner et al., 2018). This rise in global temperatures is the greatest threat to human health (Costello et al., 2009). Human activities have contributed towards a global air temperature increase of approximately 1.5 °C from pre-industrial times (Fischer and Knutti, 2015; Change, 2018; Allen et al., 2019; Hoegh-Guldberg et al., 2019; Gillett et al., 2021). Future climate projection studies (Donat et al., 2013; Morabito et al., 2017; Chen et al., 2022; Vargas Zeppetello et al., 2022) have shown that increasing temperature shifts have already increased the frequency, intensity, and duration of heat waves, which consequently has a greater impact on population health.

The year 2019 was the second warmest year since modern temperature records (which were recorded from 1850) and the warmest in the last five years, based on the World Meteorological Organization (WMO, 2020). On the other hand, 2021 was the sixth warmest year based on the 140-year climate record data given by the National Oceanic and Atmospheric Administration (Lindsey and Dahlman, 2022). In addition, Watts et al. (2015) argued that the projected impacts of climate change represented a potentially catastrophic hazard. Moreover, increased exposure to heat can have detrimental effects on human health, resulting in increased mortality (death) and morbidity (illness) across various regions (Anderson and Bell, 2011; Haines et al., 2006; Loughnan et al., 2010; Martiello and Giacchi, 2010; Zeng et al., 2016). The detrimental influence of heat on the health and work efficiency of workers working in outdoor environments has been well documented, and two studies systematically showed that high temperatures were associated with increased rates of occupational injuries (Binazzi et al., 2019; Bonafede et al., 2016). Additionally, rising temperatures and heatwaves have had and continue to have detrimental impacts on human health, ranging from heat rashes and minor discomfort to life-threatening heat strokes (Xiang et al., 2014a; Xiang et al., 2014b; Song et al., 2017).

On March 11, 2020, the COVID-19 outbreak was classified as a pandemic by the World Health Organization. Subsequently, many nations have established specific precautions to prevent the spread of SARS-CoV-2, including the use of personal protective equipment (PPE) designed specifically for COVID-19 while engaging in a variety of outdoor and indoor activities (Chu et al., 2020). These findings show that we are constantly in the middle of overlapping heat waves and COVID-19 transmission, and the consequent use of PPE is becoming increasingly common for people, particularly health care workers (HCWs). As the most preliminary protective equipment for HCW, PPE effectively serves to prevent external viruses from entering the human body (Zhang et al., 2003). Generally, PPE includes work clothes, face shields, gloves, goggles, face masks, and shoe covers, which can put great stress on the person wearing the PPE, both physically and psychologically. A common problem with disposable PPE is its poor thermal comfort level, whether worn indoors or outdoors (Laird et al., 2002; Rissanen et al., 2008; Loibner et al., 2019). Moreover, both general public and professional workers are likely to experience critical heat stress from PPE use, which adversely affects their health, productivity, judgment, and mood (Lee et al., 2020; Davey et al., 2021; Morabito et al., 2020). Researchers have extensively studied PPE, particularly its material and design aspects and practical applications. Some researchers have analyzed the thermal balance of people wearing protective clothing, temperature regulation, and heat transfer in high-temperature environments to provide relevant references for designing protective clothing and developing heat transfer models (Holmer, 2006; Zhang et al., 2021; Udayraj et al., 2016); moreover. The impacts of the design and material components of protective garments on comfort have been investigated previously (Cao and Cloud, 2011; Su et al., 2021). Some studies have focused on the design, development, and application of cooling garments to mitigate occupational heat stress (Del Ferraro et al., 2021; Morris et al., 2020; Del Ferraro et al., 2022; Butts et al., 2017). Other studies have focused on the implications of protective garment features, particularly the layers, mass, and fitting of protective garments, on metabolic rates while performing outdoor activities (Dorman and Havenith, 2009; McLellan and Havenith, 2016; Renberg et al., 2020; Rintamaki, 2005). In addition, using a climatic chamber, the effect of PPE use on the thermal response and work efficiency of workers has been studied under different climatic parameters, and different heat stress indices have been developed (Chong et al., 2018; Du et al., 2019; Sakoi and Mochida, 2013; Zwolińska and Bogdan, 2012). The wet-bulb globe temperature (WBGT) and predicted heat strain (PHS) have been widely used in the field of occupational heat stress assessment heat stress indices (Gao et al., 2018).

After the COVID-19 outbreak, HCWs started wearing PPE while working to minimize the risk of infection, both indoors and outdoors, and the consequent adverse effects of wearing PPE have raised major concerns. Additionally, various symptoms of discomfort and reactions to physiological parameters have been observed (Battista et al., 2021; Choudhury et al., 2020; Doğan et al., 2022; Jafari et al., 2021; Navarro-Triviño and Ruiz-Villaverde, 2020; Sharma et al., 2021). During the COVID-19 pandemic, several efforts focused on the use of questionnaires to assess the perceived level of heat stress and its consequences among workers in the healthcare and general work sectors (Tang et al., 2023; Lee et al., 2020; Davey et al., 2021; Messeri et al., 2021; Bonafede et al., 2022).

Since the outbreak of the COVID-19 pandemic, nucleic acid collection from medical personnel has become an integral part of strategies against COVID-19. While collecting nucleic acids, HCWs must wear PPE to prevent viral infections. Since the declaration of the pandemic, HCWs have often collected nucleic acid samples in semi-open transitional spaces. However, despite their increasing importance, studies on the responses of thermal comfort and physiology for HCWs operating in outdoor building environments with hot and humid conditions are few, especially when wearing PPE. Further studies are needed to address this aspect. In this study, an experimental field study was conducted aiming at investigating the physiological responses, thermal comfort, and thermal stress of HCWs wearing PPE while collecting nucleic acid samples (a light work activity) in a semi-open transition space. Overall, this study contributes to our understanding of the thermal response, including thermal perception and physiological responses, of critical care workers working in semi-open transition spaces using personal protective equipment, with the aim of increasing the perception and knowledge of heat stress in the workplace, mitigating heat stress to increase comfort levels and informing management and interventions for heat stress.

2. Methodology

The basis of this study entails the use of objective thermal-environment parameter measurements and subjective questionnaires. The use of subjective questionnaires was not possible in this study, as they would have interfered with the work of HCWs. Nevertheless, based on the previous studies and inspired by the used methods (Fanger, 1970; de Dear et al., 2013; Doohan et al., 2022; Xi et al., 2012), when experimental investigations cannot be completed in a real operating environment, inviting volunteers and simulating the operating environment is valid alternative approach. This method allows for an accurate simulation of the working environments, allowing for the acquisition of results that can then be applied in real-world settings. Therefore, we conducted a field experiment involving school students as volunteers, to simulate the collection of nucleic acid samples while completing a subjective questionnaire. The PPE components used were disposable and included single-layer medical protective clothing (MDPC), medical N95 masks, and medical gloves. The material of MDPC in this study was PP + PE-coated nonwoven fabric, and the other performance indicators met the requirements of GB19082–2009. More detailed information about PPE components is provided in Table 1. According to a study (Niu et al., 2021), the thermal resistance of MDPC with typical summer wear is about 1.71 ± 0.05 clo and, the thermal resistance of the mask is about 0.17 clo (Oner et al., 2022).

2.1. Meteorological conditions of the survey area

The experimental field investigation was conducted in Guangzhou in September 2021. Guangzhou (112–114.2°E, 22.3–24.1°N) is in a Hot

Table 1
Detailed information of the PPE components.

PPE components	Material	Size	Thermal resistance (clo)	Reference standards
MDPC	PP + PE coated nonwoven fabric	Small:165/120A Large:175/130A	1.71 ± 0.05 (Niu et al., 2021)	GB19082–2009
Medical N95 masks	inner layer: spunbond non-woven fabric middle layer: hot air non-woven fabric and two-layer melt blown non-woven fabric outer layer: spunbond non-woven fabric	≥14 × 14 cm	0.17 (Oner et al., 2022)	GB19083–2010
Medical gloves	PVC, rubber, etc.	Length:95 ± 5 mm Width: ≥ 230 mm	–	GB10213–2006

Summer Warm Winter (HSWW) area (Fig. 1), which is typically associated with long hot summers. The monthly mean temperatures in July and August were higher than 28 °C (monthly mean highest temperature > 33 °C). Relative humidity (RH) has a monthly average value of approximately 80 % in these months. Such climatic conditions tend to result in average heat conditions, which in summer are dominated by both moderate and intense heat stress. In this study, WBGT was used as an index to assess the thermal stress at the survey site. According to data obtained from Guangzhou Weather Station, the average daily outdoor air temperature in September ranged from to 27.7–33.1 °C and the average monthly temperatures was 30.5 °C (Fig. 2). Moreover, the relative humidity varied between 60 % and 84.7 % on average on a daily basis, and 71 % on a monthly basis. Hence, Guangzhou is a hot and humid place even in September.

2.2. Measured parameters and instruments

This study was performed at the end of Sep. 2021 in Guangzhou. Two types of parameters were measured in the subjects: environmental and

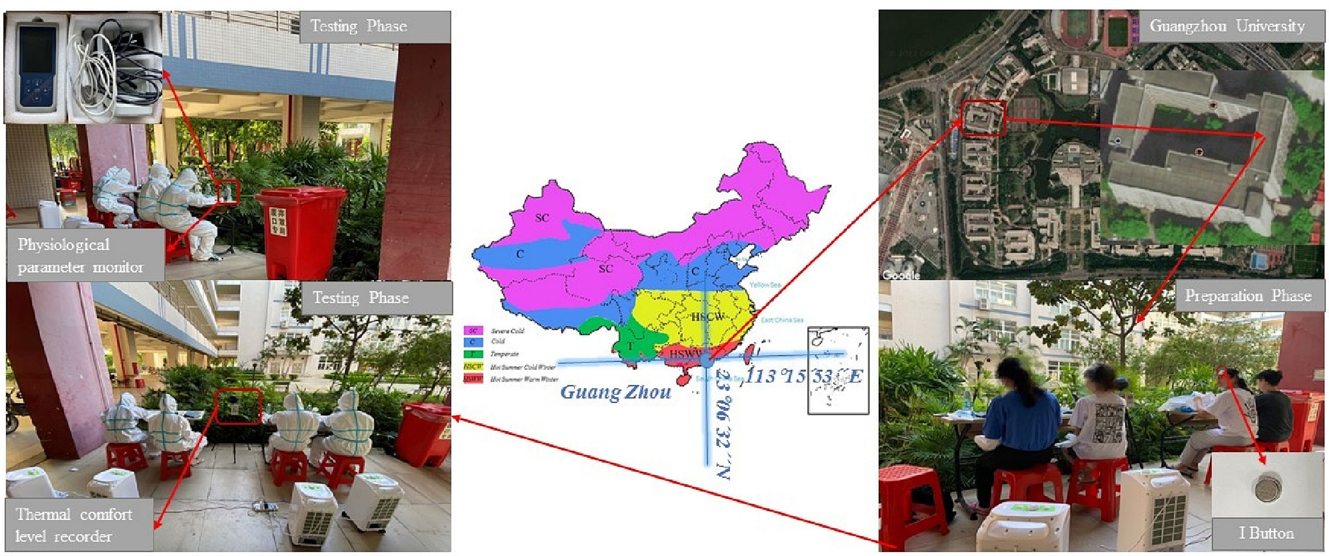

Fig. 1. Experimental field site.

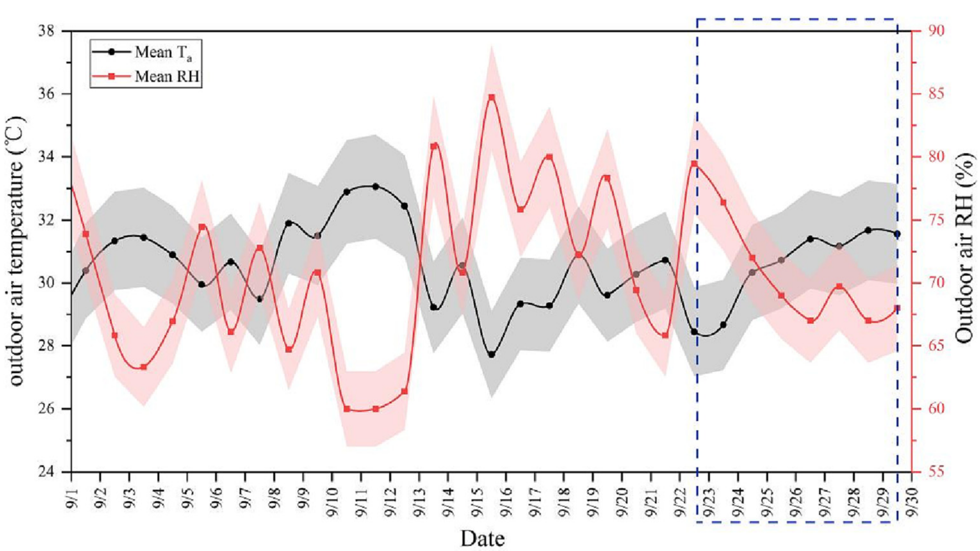

Fig. 2. Guangzhou's outdoor environmental thermal parameters in September 2021.

Table 2
Details of the instruments used in this study.

Instrument	Type	Parameter	Measurement Range	Accuracy	Sampling Rate (s)
Universal air velocity recorder	WFWZY-1	V_a (m/s)	0.05–5.00 m/s	5 % ± 0.05 m/s	30
Thermal comfort level recorder	SSDZY-1	T_a (°C)	−20 – +80 °C	±0.3 °C	30
		RH (%)	0.01–99.9 % RH	±2 % RH (10–99 % RH)	30
		T_g (°C)	−20 – +80 °C	±0.3 °C	30
iButton	DS1922L	T_{sk} (°C)	−40 – +85 °C	±0.1 °C	30
	DS1923	T_a	−40 – +85 °C	±0.1 °C	30
		RH	0–100 % RH	±5 % RH	30
Infrared tympanic thermometer	TB-300	T_{ac} (°C)	32.0–42.2 °C	±0.2 °C	1
Finger clip heart rate monitor	YX306	HR (bpm)	25–250 bpm	±1 bpm	1
Physiological parameter monitor	KMI605C	$P_{ET}CO_2$ (kpa)	0–19.95 kpa	±5 %	10
		SpO_2 (%)	50–70 %	±2 %	10
		RF (bpm)	3–150 bpm	±1 bpm	10

physiological. During the experiment, the measured environmental parameters were air temperature (T_a), relative humidity, globe temperature, and air velocity (V_a), which were automatically logged by a thermal comfort logger. Additionally, the T_a and RH of the micro-environment between the PPE and the human body were measured and recorded using two iButton (DS1923) sensors embedded in specific clasps and then hung with pins roughly at the chest and thigh positions of the protective suit, respectively. The following six physiological parameters were also measured in the subjects: T_{ac}, T_{sk}, HR, RF, $P_{ET}CO_2$, and SpO_2. T_{sk} was measured using an iButton (DS1922L) thermometer; HR was measured using a finger-clip heart rate monitor; and T_{ac} was measured using an infrared tympanic thermometer. Three other physiological parameters, RF, $P_{ET}CO_2$, and SpO_2, were measured and recorded using a physiological parameter monitor (KMI605C). Table 2 presents the comprehensive information on the instruments used in the experiments. Studies (Scholkmann et al., 2021; Sultanoğlu et al., 2021) have concluded that masks are a mechanical barrier and that wearing a mask has the potential to modify respiratory function, either in terms of respiratory mechanics, altering the respiratory drive, making breathing difficult, or various respiration-linked parameters (e.g., RF, $P_{ET}CO_2$ and SpO_2). Considering that there are few studies evaluating the effects of mask use on physiological parameters, this is intended to address this knowledge gap. Moreover, T_{ac} was measured to estimate body temperature. Previous feasibility studies of infrared ear thermometers have shown that T_{ac} is the optimal parameter for representing the body's core temperature (ANSI/ASHRAE, 2017; Greenleaf and Castle, 1972; Jakobsson et al., 1992; Modell et al., 1998). Hence, the T_{ac} of the subjects was measured, as this was the most convenient and feasible parameter for estimating the body temperature.

2.3. Subjects and questionnaire surveys

A total of 32 healthy subjects, including 20 females and 12 males, participated in the field experiment after successful advertising on a university campus. The subjects were all university students who had resided in Guangzhou for at least one year. During the entire experimental testing, the subjects were exposed to semi-open transitional space conditions, seated to complete their work, and were not exposed to the sun. The semi-open transitional space mentioned in this study, also referred to as overhead, is a building space that connects outdoor and indoor areas. Its architectural feature is that it has a top structure and no surrounding structure. None of the subjects had a history of any illness (e.g., high blood pressure, asthma, or cardiovascular disease), were non-smokers, had no chronic disease, or were not taking any medication in the experiments. Table 3 lists the profiles of the participants.

Questionnaires were administered during the experimental process. The questionnaires were divided into two sections. The first section investigated thermal sensation vote (TSV), humidity sensation vote (HSV), and air movement sensation vote (MSV) under two phases: with and without PPE. The subjects' preferences and acceptability of the parameters of the ambient thermal environment were included in the second part of the questionnaire. The scale of subjective voting was consistent with the thermal environment, according to the ASHRAE-55 and ISO 7730 standards (ANSI/ASHRAE, 2017; ISO, 2005). The conventional seven-point hot-feeling scale ranged from −3(cold) to +3(hot). Considering that HCWs with PPE work in an outdoor built environment of humid and hot conditions, the limits of the 7-point sensation scale should be considered. Therefore, a 9-point thermal and humid sensation scale was used to assess the outdoor thermal environment. A more detailed questionnaire is given in Appendix A.

2.4. Experimental procedure

The subjects provided voluntary consent before participating in the study and were informed of the nature of the study and the potential risks of working with exposure to hot weather. This study was approved by the relevant institutional review board. First, 32 subjects were assigned to a group of eight or four subjects per group. Eight experimental tests were conducted in a semi-open transitional space from September 23 to 29, 2021. The experimental schedule for each test is shown in Fig. 3. The experimental tests were conducted from 8:00 a.m. to 2:00 p.m. to 12:30 p.m. or 6:30 p.m. It lasted approximately 270 min and consisted of three phases. The stage prior to a PPE being worn was referred to as phase 1 (P1: BWP, 20 min), while the stage two which it was worn PPE referred to as phase 2 (P2: WP, 220 min), and the third phase was the rest period after the removal the PPE (P3: BWP, 30 min). The core and head temperatures in human reach equilibrium within 30 min, as reported in a previous study by Huizenga et al. (2001). Other prior studies (Chen et al., 2020; Jin et al., 2017; Zhao et al., 2022) also used–20-30 min as the preparation duration for the participants. Therefore, we used both 20 and 30 min as the preparation and recovery times for the participants, respectively.

In phase 1, the subjects remained stationary and were acquainted with the PPE. In phase 2, subjects wore PPE and performed a simulation of the nucleic acid collection task; they were seated and instructed to complete the nucleic acid sample collection every 2–3 min, which included the three main steps of pre-sampling disinfection, pharyngeal swab sampling,

Table 3
Profile of the subjects.

Gender	Sample size	Average age (y)	Average height (cm)	Average weight (kg)	Average BMR (kcal/day)	Average BMI
Female	20	20.8 ± 0.8	160.3 ± 5.1	51.5 ± 8.0	1340.1 ± 83.6	20.0 ± 2.5
Male	12	23.4 ± 1.3	171.5 ± 5.9	61.5 ± 5.7	1597.1 ± 89.7	21.3 ± 2.6
Average	–	22.1	1.66	56.5	1468.6	20.7

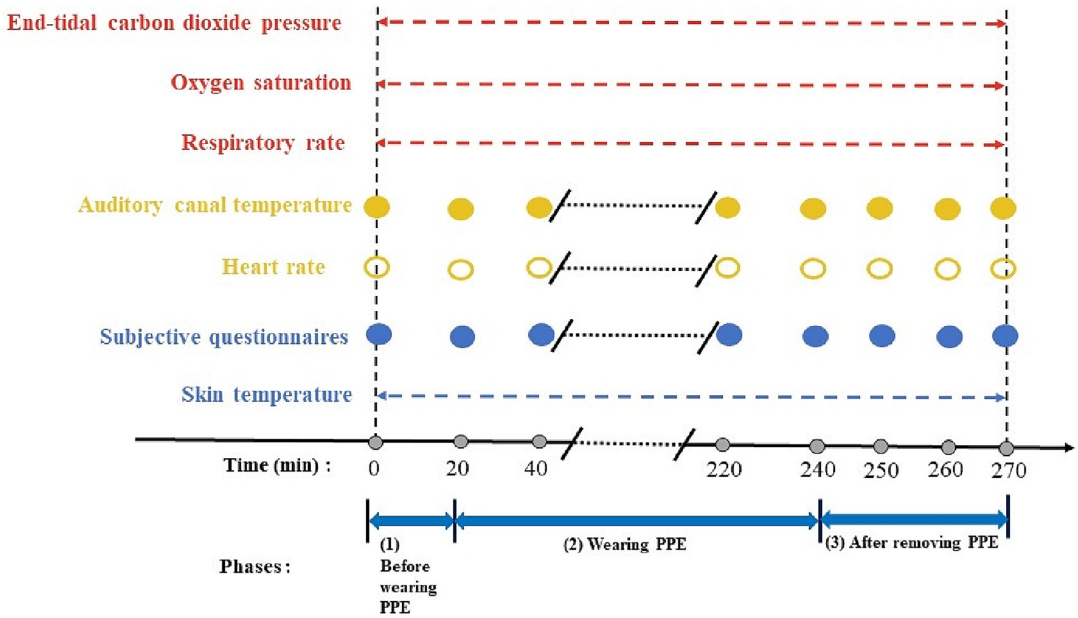

Fig. 3. Formal experimental schedule.

and loading the sample into the test tube. In the third phase, the subjects removed the PPE and took a 30-min break. Meanwhile, the subjects took approximately 3–5 min to complete the questionnaire. The questionnaire was filled out every 20 min in phases 1 and 2 and every 10 min in phase 3.

From phase 1 to the end of the testing period, seven thermometers (iButton DS1922L) were taped to the specified sites on the body of the subjects (Fig. 4) to record MST (Mean skin temperature) at intervals of 30 s. Between the protective suit and body, at the chest and thigh positions, two iButton sensors (DS1923) were embedded in specific clasps and then hung with pins roughly at the chest and thigh positions of the protective suit, respectively, to measure the T_a and RH of the microenvironment. Throughout the experiment, the physiological parameter monitors recorded the RF, $P_{ET}CO_2$, and SpO_2 of the subjects during different phases, while the thermal ambient parameters were logged automatically during the experimental period. The subjects filled out the questionnaire simultaneously, and their HR and T_{ac} were measured at intervals of 20 min during phase 1 and phase 2, and 10 min during phase 3.

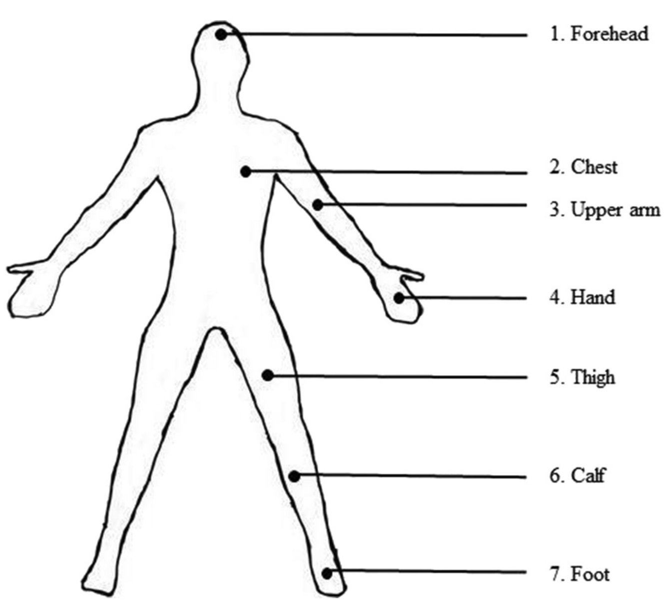

Fig. 4. Measurement points of skin temperature.

2.5. Data process

The operative temperature (T_{op}) is an index commonly applied in thermal comfort research, which considers the influences of T_a, T_{mrt} and V_a on human thermal comfort, and it was determined according to Eq. (1) (ASHRAE Standard 55, 2017)

$$T_{op} = T_a \times A + (1\text{-}A) \times T_{mrt}, \tag{1}$$

where A is a factor that depends solely on V_a. In the case of $V_a \le 0.2$ m/s, A = 0.5; for 0.2 m/s < $V_a \le 0.6$ m/s, A = 0.6; and for $V_a > 0.6$ m/s, A = 0.7. T_{mrt} was calculated by substituting T_a, T_g and V_a into Eq. (2) (ISO, 1998):

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{(1.1 \times 10^8 \times V_a^{0.6})}{(\varepsilon_g \times D^{0.4})} \times (T_g - T_a) \right]^{0.25} - 273, \tag{2}$$

where D is the globe thermometer diameter (0.15 m in this study) and ε is the emissivity (0.95 for black globe).

Wet-bulb globe temperature (WBGT), as a screening tool to assess heat stress, is one of the most widely used occupational heat stress indices worldwide. According to standard methods (BS EN ISO 7243, 2017), the WBGT can be calculated inside and outside a building without solar radiation using the following variables:

$$WBGT = 0.7T_{nw} + 0.3T_g, \tag{3}$$

where T_{nw} is the natural wet-bulb temperature (calculated with T_a and RH), and T_g is the temperature in the center of a 0.15 m diameter black globe.

In general, the MST is derived by multiplying the product of a limited number of local skin temperatures and the associated weighted coefficients. The skin temperatures from seven sites in each subject were measured. Seven skin thermometers (iButton DS1922L) were attached to the chest, forehead, upper arms, hands, thighs, calves, and foot (Fig. 4). The skin temperature was then recorded at 30-s intervals during the test. MST was calculated using Dubois' seven-point method (Dubois and Dubois, 1989) with seven skin temperature segments (1–7 being defined as head, torso, arm, head, thigh, calf, and foot), as shown below:

$$MST = 0.07T_1 + 0.35T_2 + 0.14T_3 + 0.05T_4 + 0.19T_5 + 0.13T_6 + 0.07T_7, \tag{4}$$

Table 4
Thermal environmental parameters of the experiment site.

Parameters	Abbreviation (units)	Maximum	Minimum	Mean	Standard deviation
Air temperature (Micro-e)	T_a (°C)	34.3 (36.5)	29.1(29.7)	31.9 (33.1)	1.3(1.2)
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
Wet bulb globe temperature	WBGT(°C)	31.5	27.2	28.9	0.8
Relative humidity (Micro-e)	RH (%)	91.8 (95.2)	62.2 (48.5)	72.1 (68.7)	5.4 (8.7)
Air velocity	V_a (m/s)	3.78	0.12	0.64	0.55

Micro-e: the micro-environment between protective suit and human body.

2.6. Data analysis

The collected experimental data, which included the subjects' questionnaire responses and measurement of thermal ambient parameters, were imported into Excel. Classification and ranking of the data were then performed. Linear regression was used to determine the neutral temperature and responses of physiological parameters to environmental parameters. Preferred and acceptable temperatures were determined using probability and linear regression analyses, respectively. In fact, occupants have certain requirements for the thermal environment they are exposed to achieve a thermal neutral and thermal comfort experience. Based on this, for workplaces in outdoor built environments, the assessment of occupants' acceptability (tolerance) of the thermal environment they occupy should also be considered for psychological and physiological reasons. The neutral and preferred temperatures reflect the thermal comfort requirements of the occupant, and the preferred temperature is a further analysis of the neutral temperature. In contrast to the preferred temperature, the acceptable temperature focuses more on the thermal acceptability of the environment to occupants.

All statistical analyses, consisting of linear regression formula fittings, calculations of linear regression correlation indices (R^2), and probabilistic regression analyses, were conducted using IBM SPSS Statistics 25 (IBM Corporation, Armonk, NY, USA) and Origin 2021 (Origin Lab Inc., Northampton, MA, USA). Independent sampling *t*-tests were used to determine any significant effects of PPE on subjective sensations and physiological parameters. A significance level of ≤ 0.05 indicated that there is a statistically

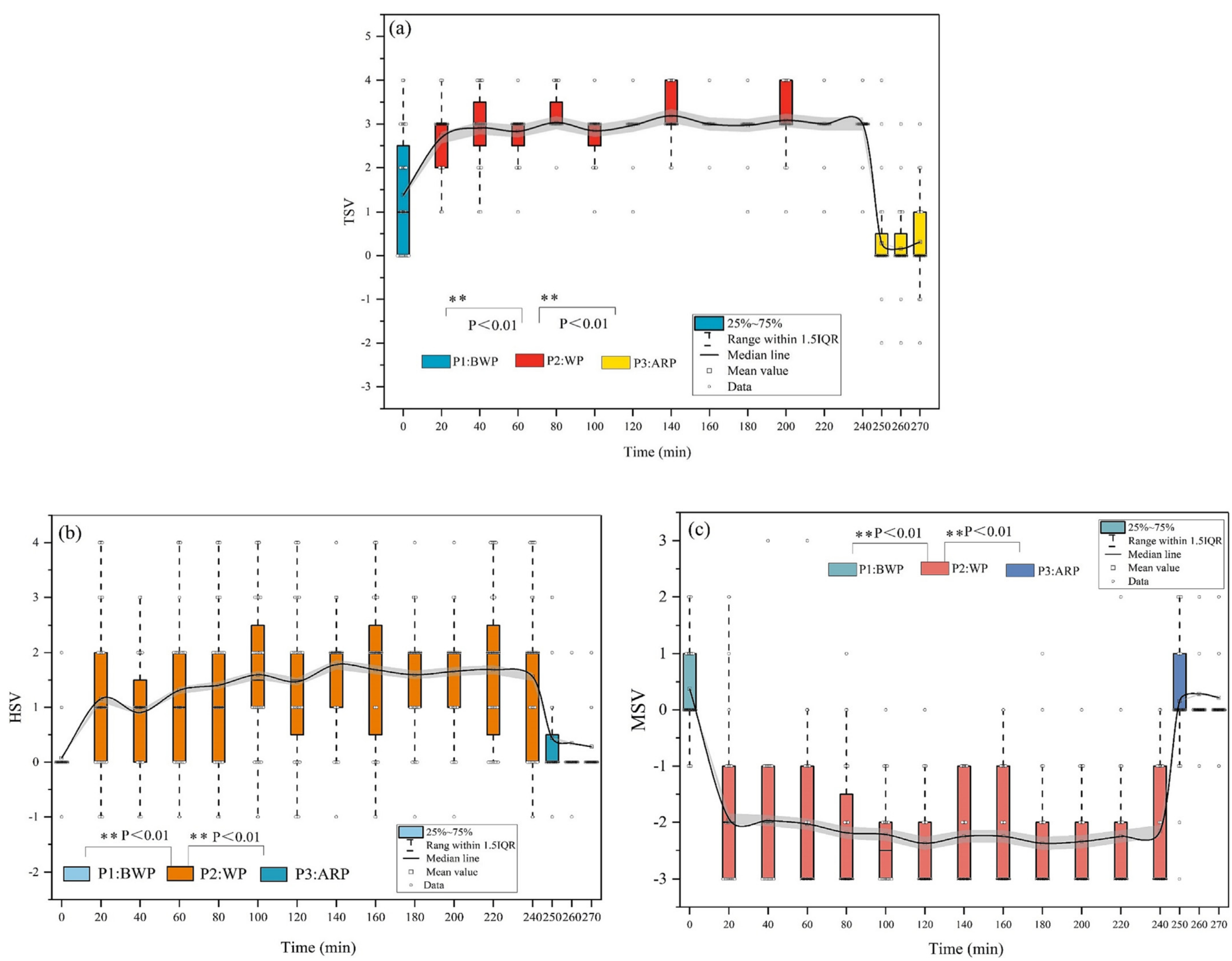

Fig. 5. Distribution of subjective sensation votes in different phases: (a) TSV, (b) HSV, and (c) MSV.

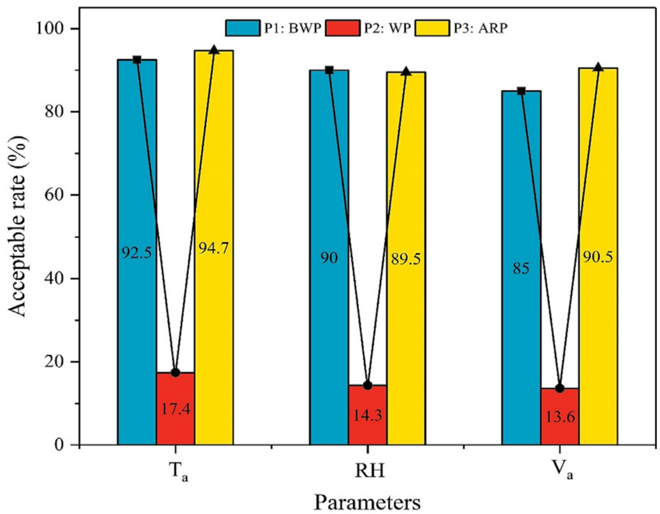

Fig. 6. Percentage distribution of thermal acceptability of thermal environment parameters in different phases.

significant difference. Figures and graphs were generated using IBM SPSS Statistics 20 and Origin 2020, respectively.

3. Results

3.1. Thermal parameters

The values of the environmental thermal parameters T_a, RH, and V_a acquired during the experiment were 29.1–34.3 °C, 69.2 %–91.8 %, and 0.12–3.78 m/s, respectively (Table 4). Based on the calculations listed in Section 2.5, the range of the mean radiant temperature was 29.3–37.5 °C, and the average value was 32.1 °C, while that of T_{op} was 29.3–35.1 °C, and the average value was 32.0 °C. The WBGT ranged from 27.2 to 31.5 °C, with a mean value of 28.9 °C. The average T_a, RH, and V_a of 31.9 °C, 72.3 % and 0.64 m/s, respectively, were above the monthly average temperature (30.5 °C) and RH (71 %), suggesting that the location of the experiment was fairly hot and humid. Moreover, the T_a and RH of the micro-environment reached maximum values of 36.5 °C and 95.2 %, respectively, with average values of 33.1 and 68.7 %, respectively.

3.2. Distribution of subjective evaluations

The distributions of the subjective sensation evaluations during different phases, including TSV, HSV, and MSV, are shown in Fig. 5. PPE significantly affects subjects' perceptions, including changes in voting values and distribution characteristics. Generally, both the MTSV and MHSV increased significantly from 1.4 to 3.0 and from 0.1 to 1.6, respectively, and the MMSV decreased considerably from 0.4 to −2.2 with PPE, implying that the subjects were in a hotter and more humid state with little airflow. Meanwhile, as the time spent wearing PPE increased, the subjects had a higher thermal sensation and humidity sensation, while the MSV was lower. It can be seen that the subject's MTSV was slightly lower in the first half of the time (Time = 20–120 min, MTSV = 2.86) while wearing the PPE than in the second half of the time (Time = 140–240 min, MTSV = 3.04). For HSV, it can be seen based on the subjects' MHSV that their HSV essentially increased with time while wearing PPE. After the subjects removed the PPE, their MTSV (0.3) was significantly lower than before they wore the PPE (1.4), which could be attributed to the contribution of the subjects' wetter skin and the local fan behind them. In the case of MHSV, subjects had a slightly lower MHSV before wearing PPE (0.1) than after removing PPE (0.3), while the reverse was the case for MMSV (0.4 vs 0.2).

Additionally, none of the subjects felt temperature neutral when wearing PPE, the percentage of subjects feeling hot along with very hot had an increase to 80.3 %, while the percentage of subjects feeling humid reached 83.2 %, including 10.9 % who felt highly humid. Moreover, the proportion of MSV for weak (−2) and very weak (−3) feeling exceeded 70 %.

The effect of using PPE on human perception was investigated using an independent sample *t*-test. The results showed a statistically significant difference between perceived voting with and without PPE ($p = 0.000$, $p < 0.05$).

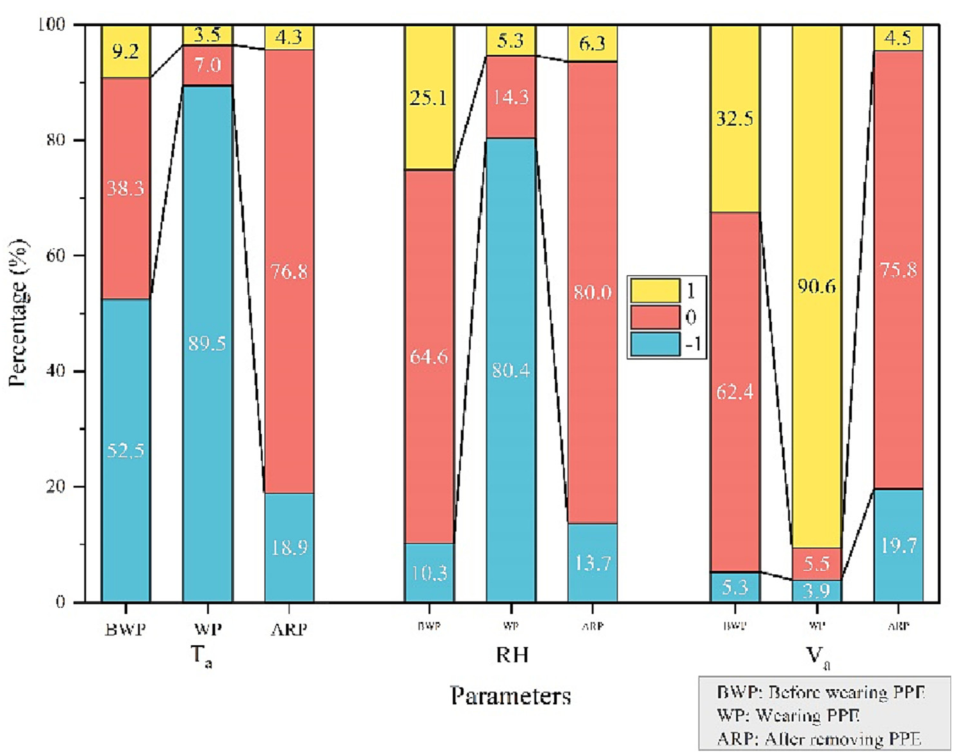

Fig. 7. Percentage distribution of thermal preferences for thermal environment parameters in different phases. − 1: lower; 0: no change; and + 1: higher.

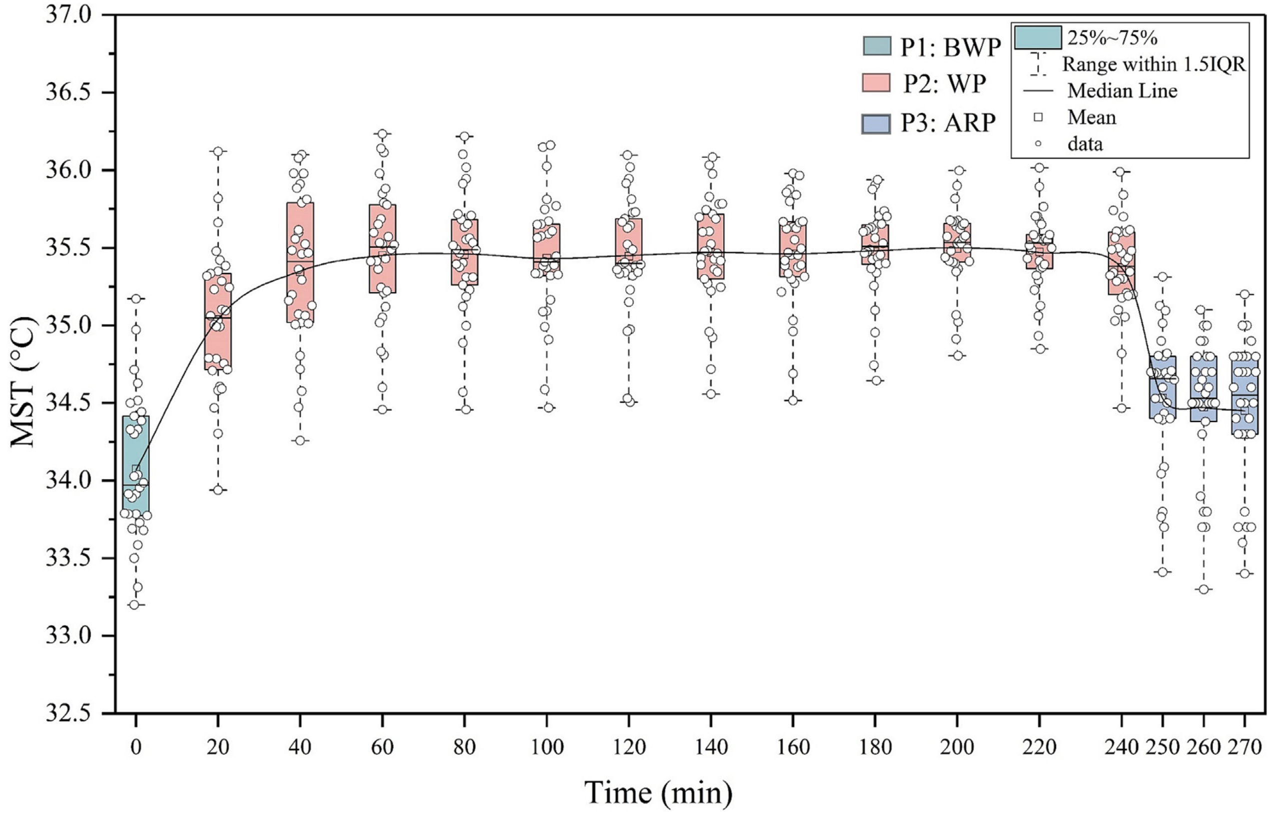

Fig. 8. Temporal changes in MST.

3.3. Impact of PPE use on thermal preference and acceptance

The acceptance rates of the thermal environmental parameters varied considerably in the three different states, as represented by the V-shaped variation in Fig. 6. Almost all the subjects reported that the thermal parameters were intolerable when wearing PPE. Accordingly, the subjects expected the thermal environmental parameters to change while wearing PPE, which could, in turn, alleviate thermal discomfort. In addition, the subjects appeared

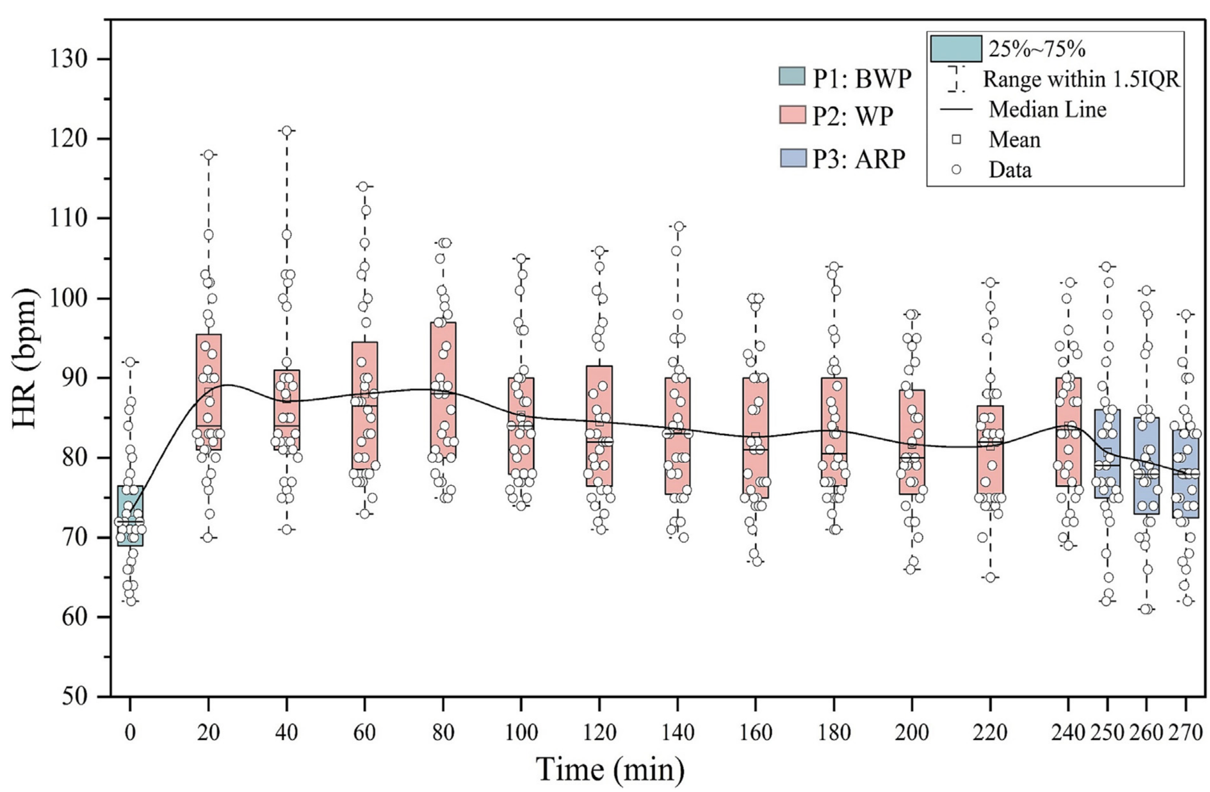

Fig. 9. Temporal changes in HR.

to be more accepting of the thermal environmental parameters after removing PPE than before wearing PPE. While wearing PPE, as shown in Fig. 7, 89.5 %, 80.4 %, and 90.6 % of the subjects preferred lower temperature, lower RH, and higher V_a, respectively, compared with 52.5 %, 10.3 %, and 5.3 %, before wearing PPE. Thus, we can infer that HCWs who wear PPE are potentially exposed to health risks and are likely to suffer from heat stress while working in hot weather conditions, even in semi-open transitional spaces.

3.4. Variations in the physiological parameters

3.4.1. Mean skin temperature

Fig. 8 shows the temporal changes in MST of the subjects. When the subjects wore PPE, their MST increased significantly, and after approximately 60 min, the MST stabilized until PPE was removed. When the subjects removed the PPE and rested, the MST decreased and gradually stabilized at a slightly higher value than the initial value. Before wearing PPE, there was an MST of 33.2–35.2 °C, and the average value was 34.1 ± 0.5 °C. However, the MST increased to 33.9–36.2 °C and the average value was 35.4 ± 0.4 °C while the subjects were wearing PPE. After removing PPE, the MST was 33.3–35.3 °C, and the average value was 34.5 ± 0.4 °C. In addition, the mean MST was 1.5 °C and 0.3 °C higher in subjects in phases 2 and 3 than in those in phase 1, respectively.

3.4.2. Heart rate

Fig. 9 shows the temporal changes in the HR of the subjects. During the first 20 min after the subjects wore PPE, their HR significantly increased. However, it slightly decreased over the next 20 min. After an additional 40 min of gradual increase, a gradual decrease was observed. Before wearing PPE, the HR of the subjects was 62–92 bpm, with an average of 73 ± 7 bpm. When the subjects wore PPE, their HR increased to 65–121 bpm, with an average value of 85 ± 9 bpm. After removing PPE, the HR was 61–104 bpm, with an average of 79 ± 10 bpm. These results imply that PPE use elevated HR, as it was shown to be approximately 12 bpm higher while the subjects were wearing PPE than before they wore PPE.

3.4.3. Auditory canal temperature

Fig. 10 shows the temporal changes in T_{ac} of the subjects. When wearing PPE, T_{ac} increased rapidly and stabilized after 40 min until PPE was removed, during which T_{ac} decreased sharply and gradually over 30 min. Before wearing PPE, T_{ac} ranged between 35.6 and 36.8 °C, with an average value of 36.1 ± 0.3 °C. However, when the subjects wore PPE, it increased to 36.3–37.8 °C, with a mean value of 37.2 ± 0.3 °C. After removing PPE, the T_{ac} ranged between 35.2 and 37.4 °C, with a mean value of 36.6 ± 0.5 °C. The mean T_{ac} of the subjects in Phases 2 and 3 was 1.1 °C and 0.5 °C higher than that of Phase 1, respectively.

3.4.4. Respiratory rate, end-tidal carbon dioxide pressure, and oxygen saturation

Throughout the experiment, RF, $P_{ET}CO_2$, and SpO_2 of the subjects were measured and recorded using a physiological monitor. The corresponding results are represented as box plots over time in Figs. 11, 12, and 13.

Fig. 11 shows the temporal variations in RF. Within 40 min of wearing PPE, RF noticeably increased. After a slight decrease, it stabilized and was above the baseline value. Before wearing PPE, the observed RF was 6–28 bpm, with a mean of approximately 13 ± 4 bpm. When the subjects rested for 30 min and removed the PPE, their RF was 8–38 bpm, with a mean of 16 ± 4 bpm. Nevertheless, while wearing PPE, RF was 7–38 bpm, with a mean value of approximately 18 ± 5 bpm.

Fig. 12 shows the temporal variations in $P_{ET}CO_2$. Similar to RF, the $P_{ET}CO_2$ was higher with PPE than without PPE. In particular, after 20 min of wearing PPE, $P_{ET}CO_2$ increased rapidly and then decreased to stabilize and subsequently remained at a level above the baseline. Moreover, after removing PPE, $P_{ET}CO_2$ had lower levels than when wearing PPE but was still above the level before the PPE was worn, which was 3.3–5.8 kPa, with a mean $P_{ET}CO_2$ of approximately 4.4 ± 0.3 kpa. Furthermore, during the resting period of 30 min, when PPE was removed, $P_{ET}CO_2$ was 3.5–5.8 kpa, with a mean value of 4.6 ± 0.4 kpa. Nevertheless, with PPE, $P_{ET}CO_2$ was 3.2–6.2 kpa, with a mean value of approximately 4.9 ± 0.4 kpa.

Fig. 13 shows the temporal variations in SpO_2. When the PPE was worn, SpO_2 decreased. Before wearing PPE, SpO_2 was 96–99 %, with a mean SpO_2

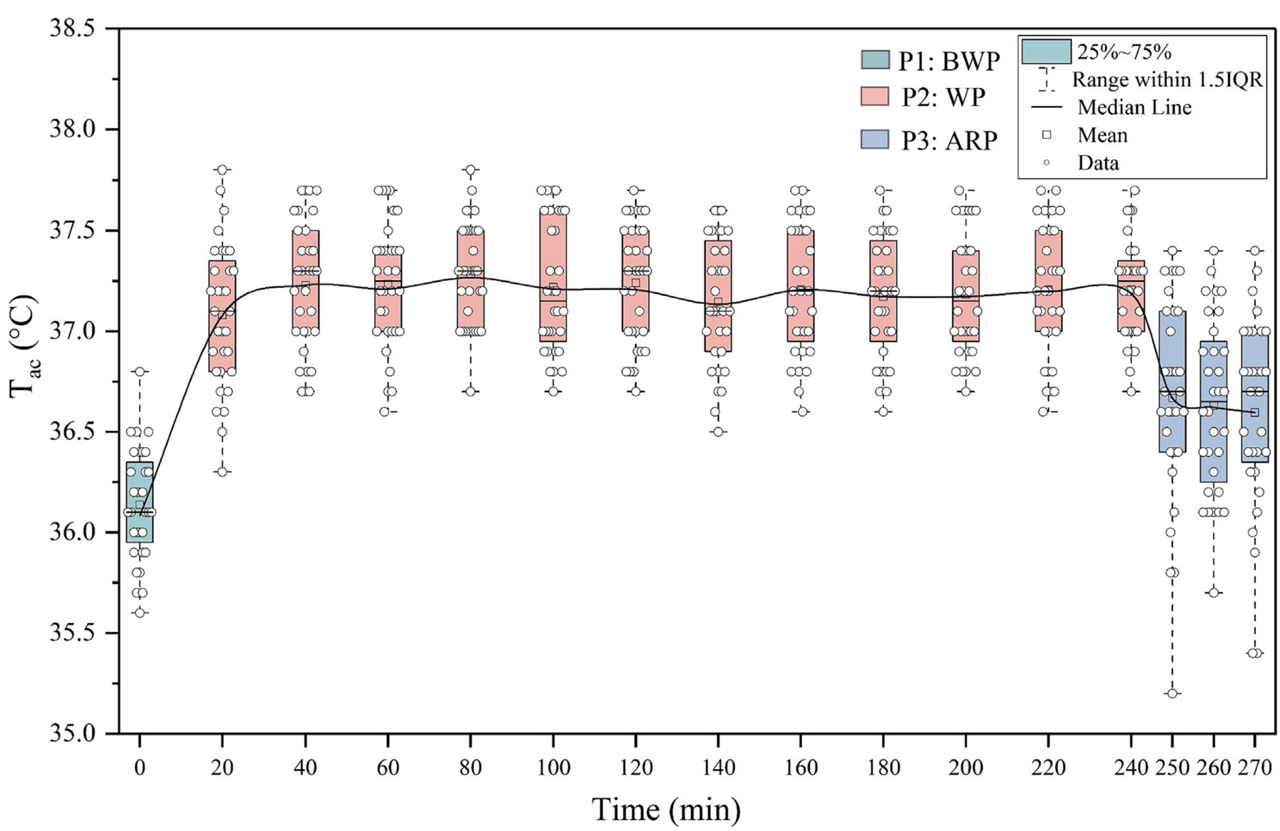

Fig. 10. Temporal changes in T_{ac}.

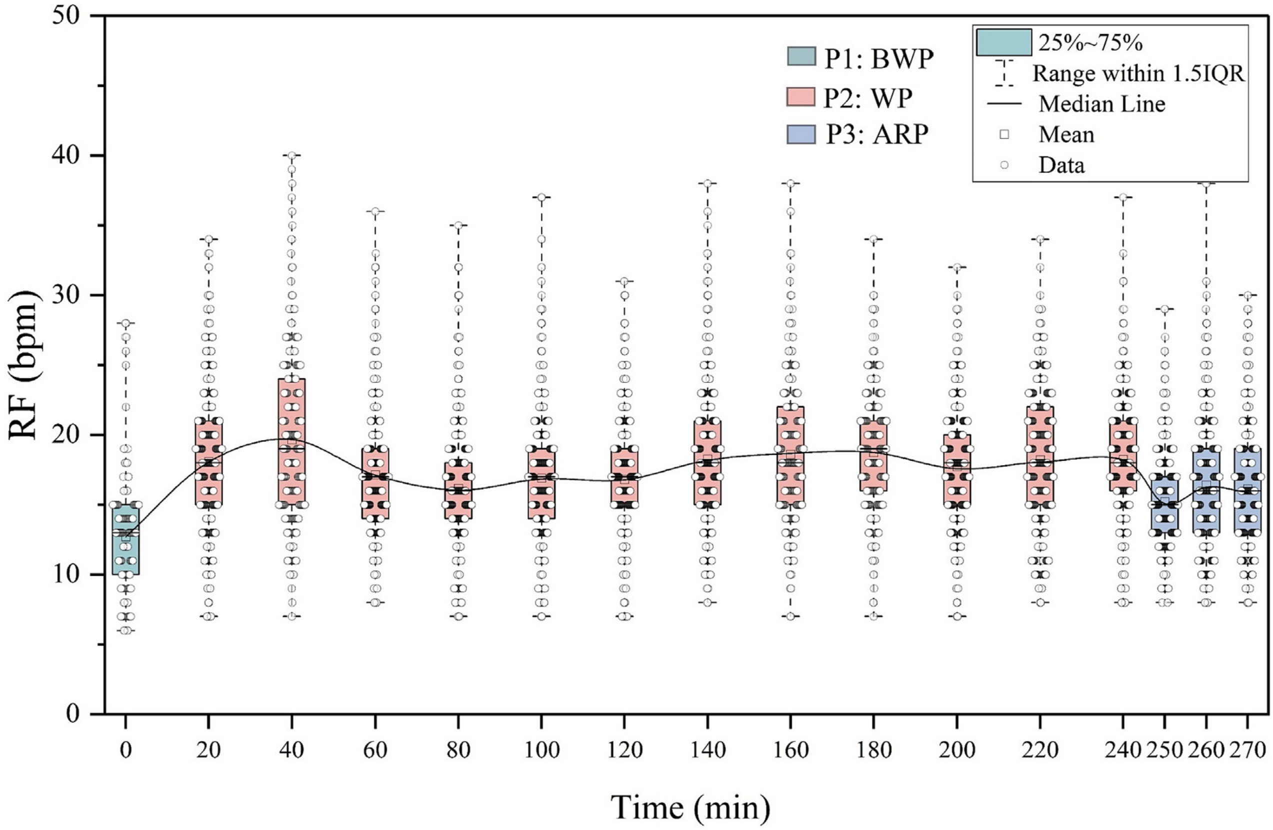

Fig. 11. Temporal changes in RF.

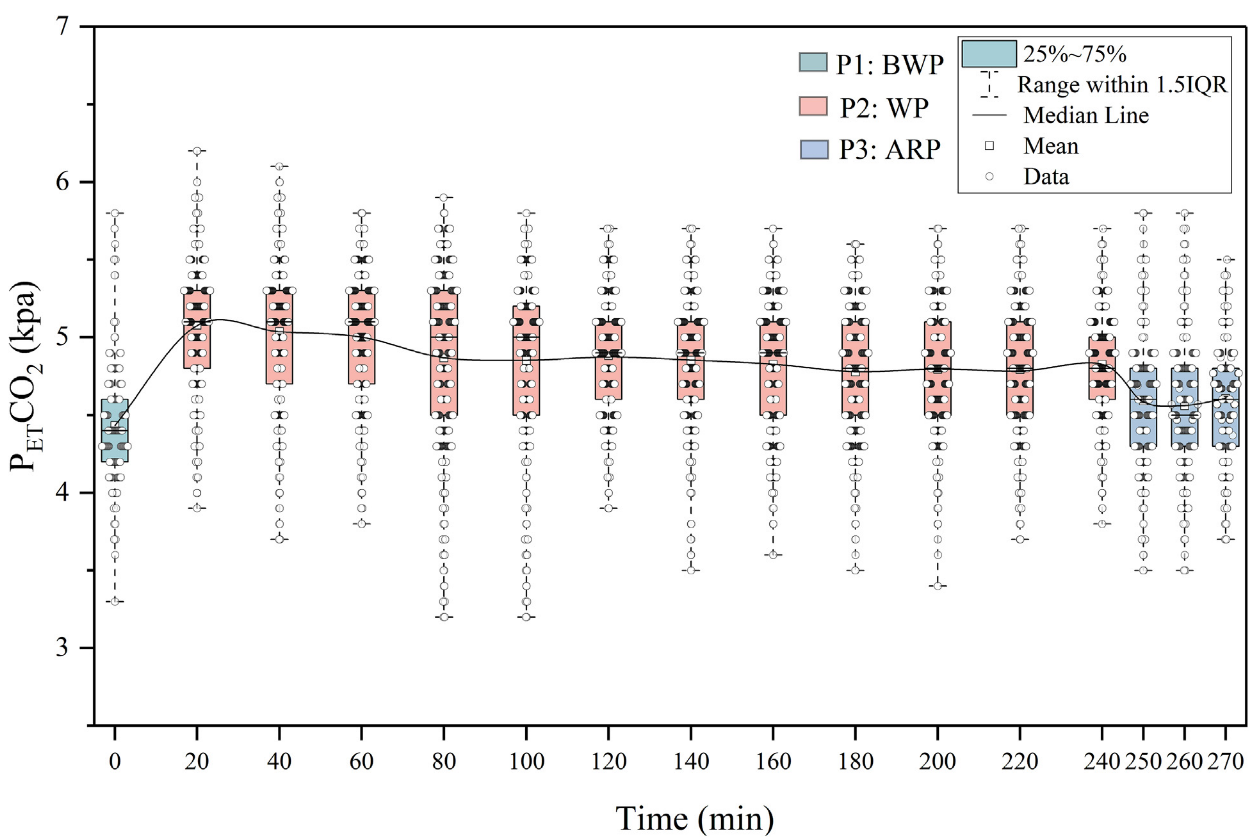

Fig. 12. Temporal changes in $P_{ET}CO_2$.

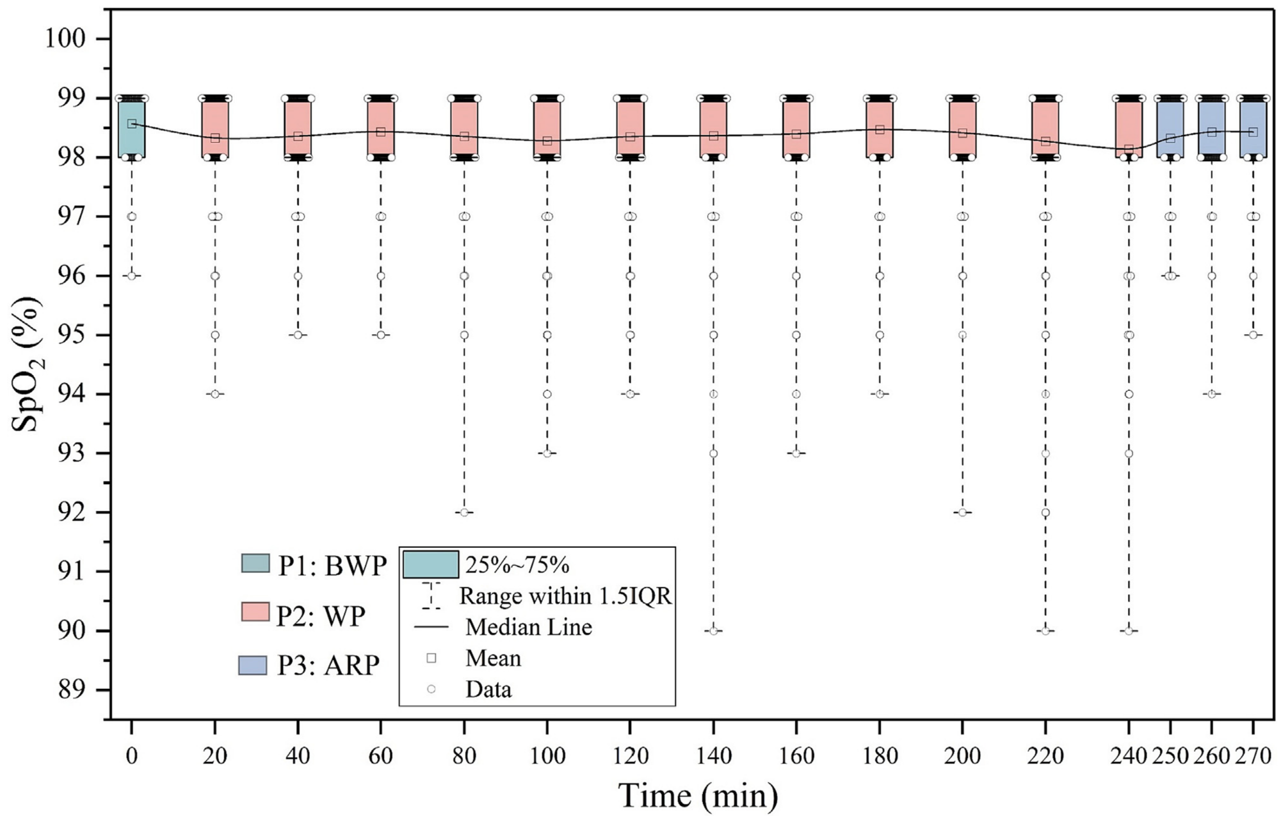

Fig. 13. Temporal changes in SpO_2.

value of 98.57 ± 0.62 %, whereas it was 90–99 % with a mean value of 98.34 ± 0.89 % when PPE was worn. Furthermore, after removing PPE, SpO_2 was 94–99 %, and the mean SpO_2 value was 98.39 ± 0.89 %. Notably, the SpO_2 of the subjects remained below the baseline levels while wearing PPE and during the resting period when the PPE was removed.

To determine the impact of PPE use on human physiological responses and status, the physiological parameters of subjects with and without PPE were analyzed using an independent sample *t*-test, and the corresponding results are plotted in Table 5. As indicated by the *p*-value, the physiological parameters with and without PPE showed statistically significant differences.

3.5. Correlation between physiological parameters and WBGT

Linear regression was performed between the physiological parameters of HR, MST, T_{ac} and WBGT. The corresponding results are presented in Fig. 14 (a)–(c), and the regression models are presented in Table 6. The physiological parameters and WBGT were strongly correlated ($r > 0.7$). Furthermore, the HR, MST, and T_{ac} of the participants increased with increasing WBGT. The slopes of the equations represent the sensitivity of the physiological parameters to alterations in WBGT. The slopes of the regression equations between MST and T_{ac} were lower when the subjects wore PPE than when they did not wear PPE, whereas the slopes of HR were higher when the subjects wore PPE than when they did not wear PPE but lower than those after removing PPE. Based on the values of the slope of the physiological parameters with WBGT change, a stronger response of heart rate than both MST and T_{ac} was inferred while wearing PPE, and the smaller variations in MST and T_{ac} were indicative of a reduction in the effectiveness of human thermoregulatory and defense mechanisms intended to prevent heat stroke.

Table 5
Detailed information on the t-test.

Physiological parameters		F	Significance	t	*P* (Sig, 2-tailed)	Mean difference
T_{ac}	EVA	43.791	0.000	−12.686	0.000	0.546
	EVNA			−10.130	0.000	0.546
MST	EVA	15.550	0.000	−23.611	0.000	1.027
	EVNA			−21.089	0.000	1.027
HR	EVA	0.772	0.380	−7.859	0.000	8.357
	EVNA			−7.714	0.000	8.357
$P_{ET}CO_2$	EVA	11.069	0.001	−23.320	0.000	0.321
	ENVA			−24.186	0.000	0.321
RF	EVA	10.980	0.001	−13.363	0.000	4.227
	EVNA			−16.106	0.000	4.227
SpO_2	EVA	2.816	0.093	−2.738	0.006	0.076
	EVNA			−2.992	0.003	0.076

EVA = equal variances assumed; EVNA = equal variances not assumed. Note: p(Sig.) < 0.05 is significant.

3.6. Gender differences

Questionnaire data and physiological parameters collected during the experiment were obtained from 20 female and 12 male participants. To determine whether the obtained results were statistically significantly different for the two genders, independent sample *t*-tests were conducted using SPSS software, controlling for the same amount of data for both males and females in the analysis (Table 7). According to the results, there was a significant difference between the two sexes in terms of subjective perception evaluation. For physiological responses, there were no significant differences in T_{ac}, MST, and SpO_2 between the sexes, while there were significant differences in HR, $P_{ET}CO_2$ and RF between the two sexes. Nevertheless, it can be believed that such results are attributable more to the different genders than to the difference in the number of subjects between the two genders.

3.7. Preferred temperature and neutral temperature

The preferred and neutral temperatures reflect the occupant's thermal comfort requirements in the thermal environment. The "neutral temperatures" indicate the temperature at which people feel thermal neutrality and

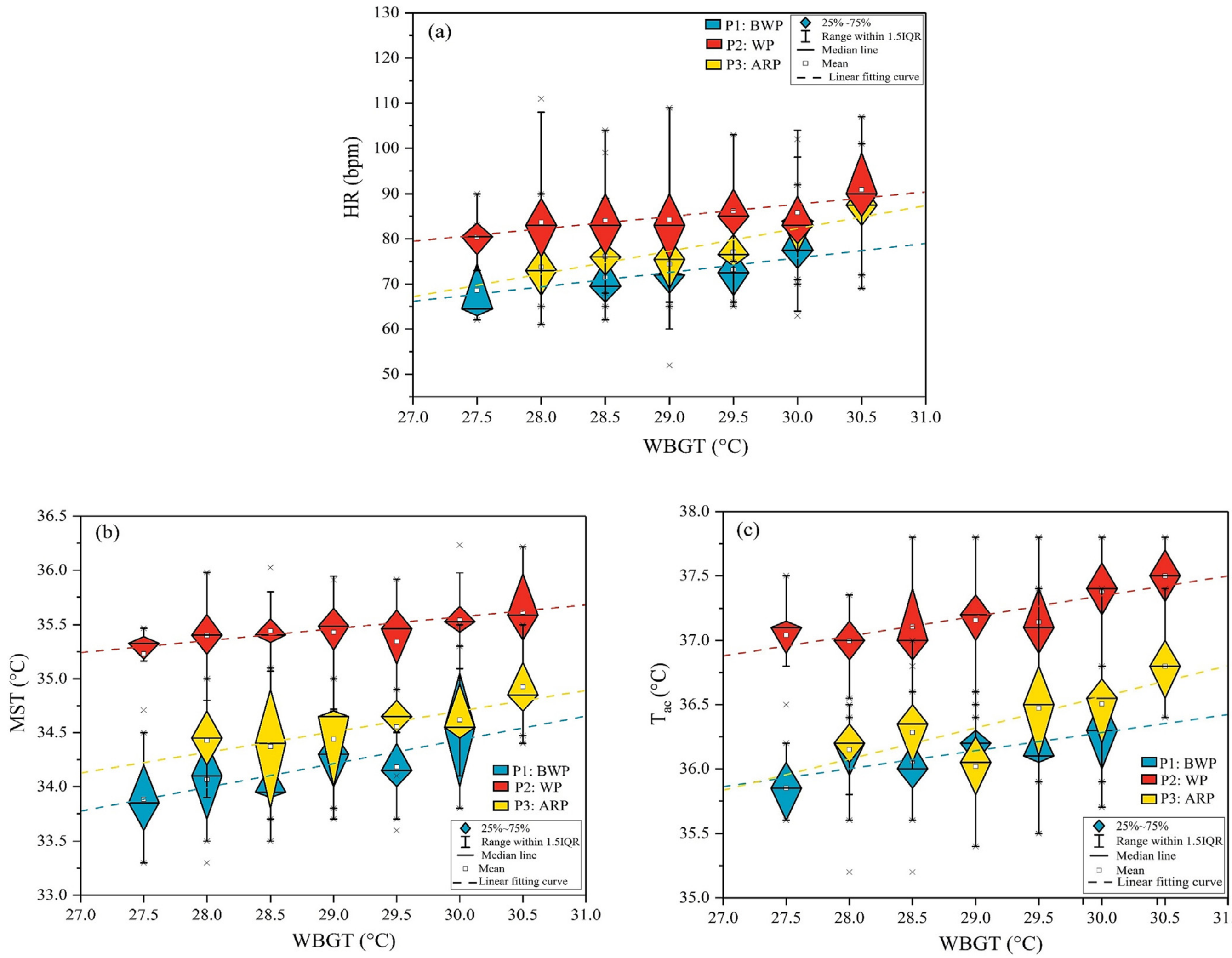

Fig. 14. Relationship between physiological parameters and WBGT: (a) HR, (b) MST, and (c) T_{ac}.

the neutral temperatures were usually determined by analyzing the relationship between MTSV and temperatures. People in hot climates may prefer slightly cooler than neutral sensations, whereas people in cold climates may prefer slightly warmer than neutral sensations. It can be argued that the preferred temperature is the result of further analysis of the neutral temperature, and that the "preferred temperatures" are usually determined by analyzing the relationship between thermal preference votes and temperatures.

During the experiment, the thermal preference votes of the subjects and probabilistic regression analyses were performed on the corresponding T_{op} and WBGT values to obtain the curves of the preferred temperatures. The temperatures corresponding to the intersection of the two curves represent the preferred temperatures of the subjects. Fig. 15 (a-d) show the probability curves of $T_{op}/WBGT$ with and without PPE, respectively. The relationship between $T_{op}/WBGT$ and MTSV was determined using linear regression models, as shown in Fig. 16. According to the linear regression

Table 6
Detail information of linear regression.

Physiological parameter	Phase	Equation y = physiological parameter x = WBGT	R^2
HR	Before wearing PPE	y = 3.2225× − 20.8775	0.7332
	While wearing PPE	y = 2.7372× + 5.5828	0.8345
	After removing PPE	y = 5.0464× − 69.06	0.7248
MST	Before wearing PPE	y = 0.22× + 27.8333	0.8236
	While wearing PPE	y = 0.1103× + 32.2648	0.8292
	After removing PPE	y = 0.191× + 28.9692	0.7837
T_{ac}	Before wearing PPE	y = 0.1406× + 32.0652	0.7751
	While wearing PPE	y = 0.1547× + 32.7027	0.8411
	After removing PPE	y = 0.2425× + 29.2862	0.7457

Table 7
Detail information of t-test analysis for gender differences.

Parameters		F	Significance	t	P (Sig, 2-tailed)	Mean difference
TSV	EVA	0.033	0.855	−2.964	0.003	0.426
	EVNA			−2.868	0.005	0.426
HSV	EVA	4.308	0.038	−8.158	0.000	0.969
	EVNA			−7.738	0.000	0.969
MSV	EVA	5.409	0.020	3.260	0.001	0.584
	EVNA			3.040	0.003	0.584
T_{ac}	EVA	3.845	0.051	0.665	0.513	0.031
	EVNA			0.713	0.477	0.031
MST	EVA	3.736	0.54	0.284	0.776	0.423
	EVNA			0.177	0.880	0.423
HR	EVA	1.710	0.192	−3.683	0.000	3.89
	EVNA			−3.945	0.000	3.89
$P_{ET}CO_2$	EVA	9.915	0.002	−41.714	0.000	0.410
	ENVA			−40.957	0.000	0.410
RF	EVA	6.767	0.009	13.637	0.000	1.581
	EVNA			13.385	0.000	1.581
SpO_2	EVA	20.620	0.000	−0.121	0.903	0.013
	EVNA			−0.182	0.856	0.013

EVA = equal variances assumed; EVNA = equal variances not assumed. Note: p(Sig.) < 0.05 is significant.

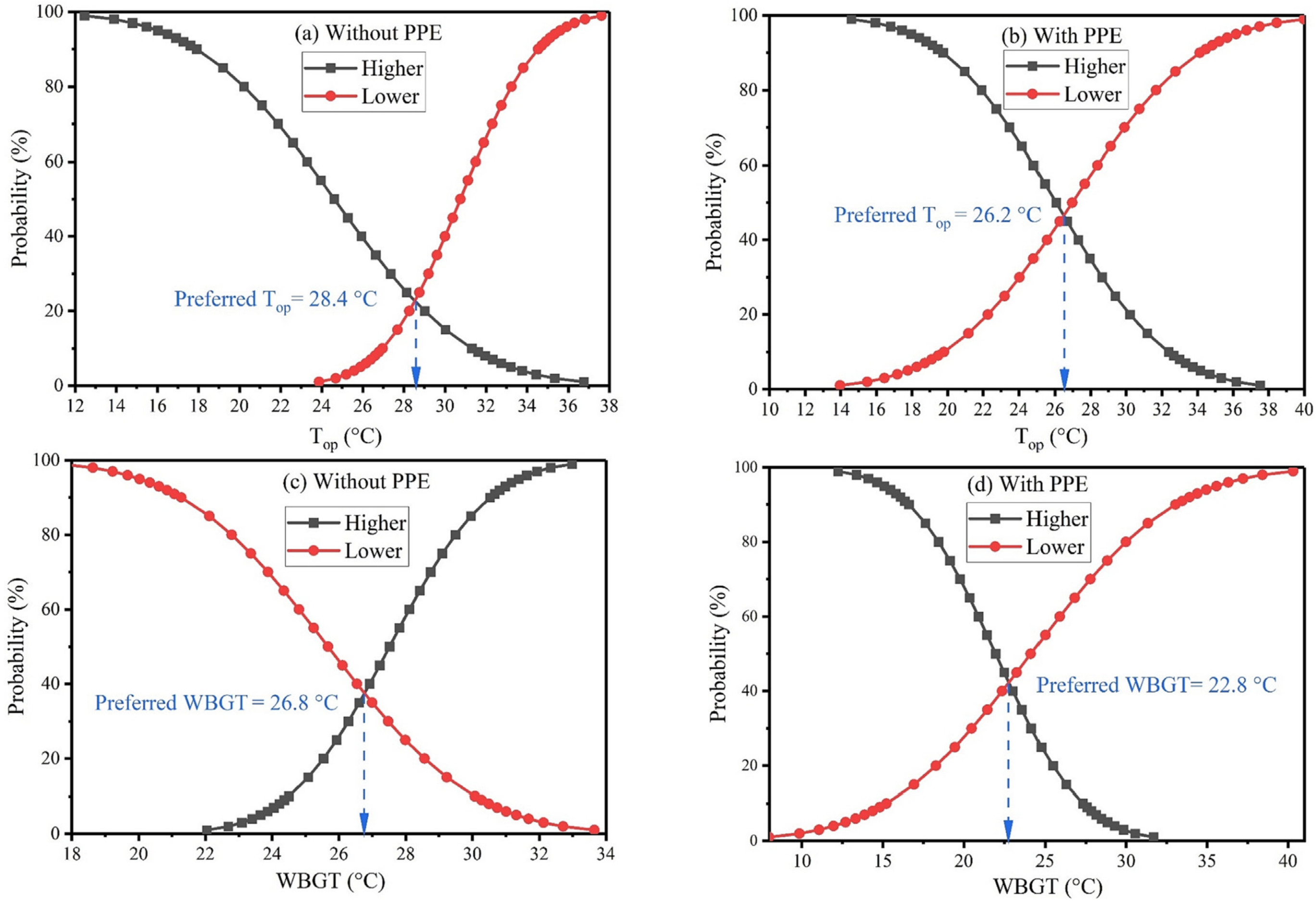

Fig. 15. Probit analysis of preferred T_{op} and WBGT: (a, c) Without PPE and (b, d) with PPE.

equation, the neutral temperature was calculated when MTSV = 0. The preferred $T_{op}/WBGT$ for subjects who were not wearing PPE was 28.4/26.8 °C, which was 2.2/4.0 °C higher than for those wearing PPE (26.2/22.8 °C). Furthermore, the neutral $T_{op}/WBGT$ (29.2/26.9 °C) was higher than the preferred temperature (28.4/26.8 °C) when the subjects were not wearing PPE. In contrast, when the subjects wore PPE, the neutral $T_{op}/WBGT$ (19.5/19.8 °C) was lower than the preferred temperature (26.2/22.8 °C). This can explain why a lower neutral temperature indicated the requirement of a higher temperature gradient to transfer more heat to the environment to achieve thermal comfort while wearing PPE in hot weather conditions.

3.8. Acceptable temperature limit

Linear regressions were performed based on the heat acceptance vote and corresponding WBGT of the subjects. Fig. 17 (a) and (b) show the linear curves of the WBGT with and without PPE, respectively. ASHRAE Standard-55 (ANSI/ASHRAE, 2017) specifies the thermal environmental conditions

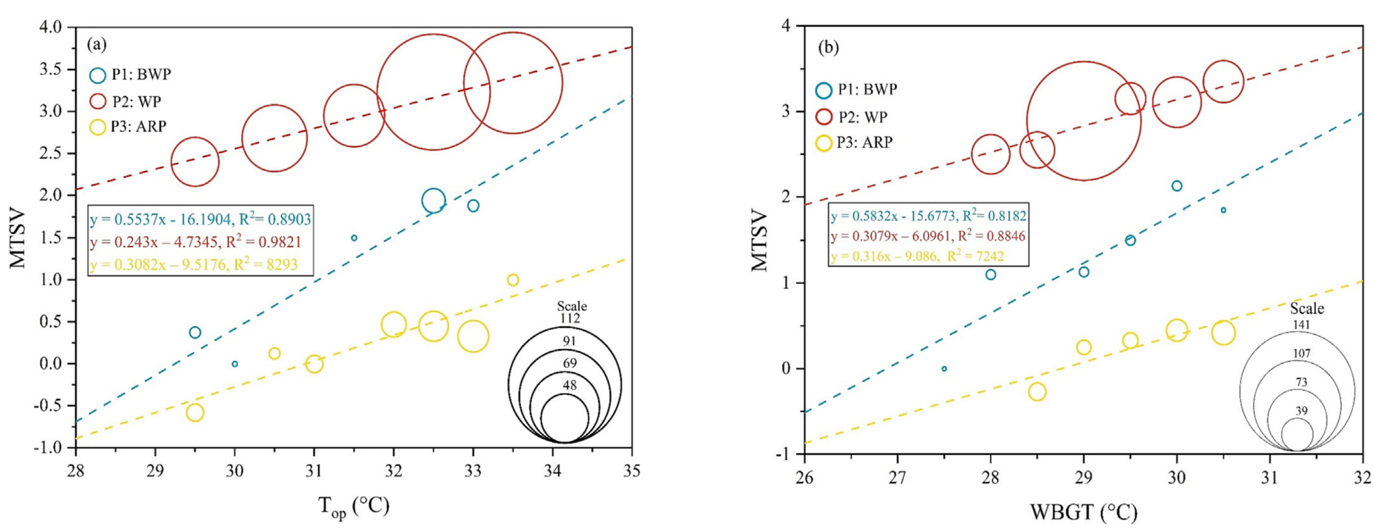

Fig. 16. Relationship between MTSV and thermal index: (a) MTSV and T_{op}; (b) MTSV and WBGT.

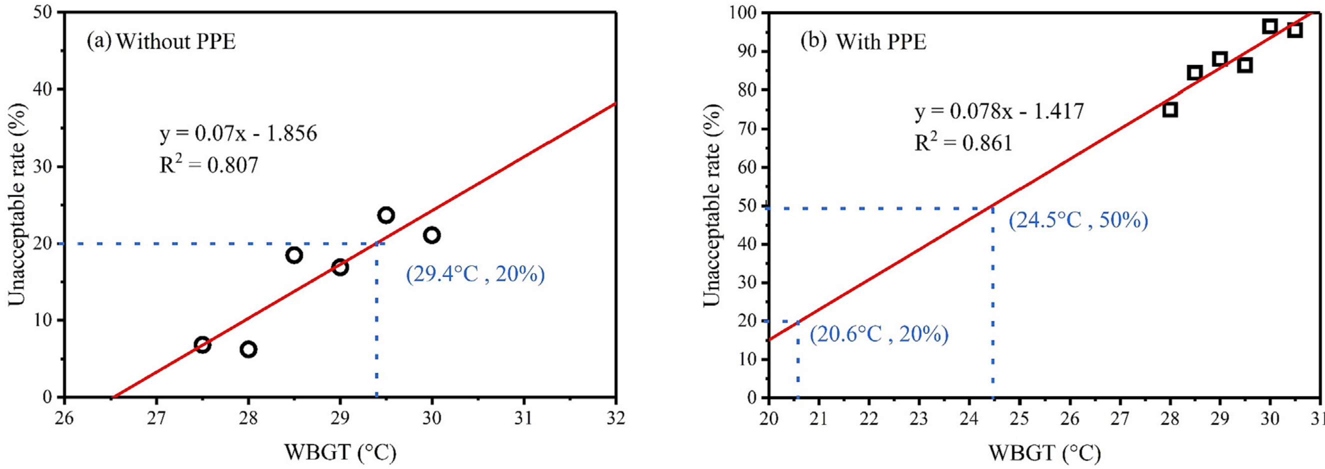

Fig. 17. Relationship between subjective thermal unacceptable rate and WBGT: (a) Without PPE and (b) with PPE.

that are acceptable to 80 % or more of the occupants of a space. Although the standard never precisely defines "acceptability," a direct assessment of thermal acceptability can be taken (voting "acceptable" or unacceptable in the questionnaire). Therefore, the acceptable temperature was calculated when unacceptable rate equals 20 % (that is, acceptable rate was 80 %). The upper limit of the acceptable temperature was used to assess the thermal acceptability of the subject to the thermal environment. As shown in Fig. 17 (a), WBGT was 29.4 °C in the subjects without PPE when the unacceptability rate was 20 %. Therefore, in this study, the acceptable WBGT limit for T_{op} was 29.4 °C without PPE.

Moreover, as shown in Fig. 17 (b), WBGT was 20.6 °C in the subjects who wore PPE when the unacceptability rate was 20 %. According to ASHRAE standard-55 (2017) for typical applications, the acceptable thermal conditions must be at least 80 %. Nevertheless, it might be debatable to consider 20.6 °C (WBGT) as the upper limit temperature, even if the subjects wore PPE. Moreover, the thermal adaptability, tolerance, and psychological factors of the participants should also be considered. Therefore, in this study, the acceptable thermal conditions were extended to an unacceptability rate of 0 %–50 % while wearing PPE. Correspondingly, the acceptable e WBGT limit was 24.5 °C when the unacceptability rate was 50 %, while the subjects wore PPE. Thus, wearing PPE lowered the threshold of the acceptable temperature.

4. Discussion

4.1. Human heat balance and thermal comfort

Humans maintain a relatively stable core temperature with a dynamic balance between internally generated heat and external heat dissipation to the ambient environment. The biophysics of the heat balance equation for the human body, which was developed to accurately reflect human energy exchanges and core temperature dynamics, has been previously applied to thermal comfort studies (Cramer and Jay, 2016; Gagge and Nishi, 2010; Garner and Fendius, 2010; Fang et al., 2019). The ability to exchange heat between the body and environment depends largely on several external parameters.

In this study, the T_a of the microenvironment ranged from 29.7 to 36.5 °C, with a mean value of 33.1 °C. Moreover, the average RH of the microenvironment and ambient environment were 68.7 % and 72.3 %, respectively. Nevertheless, ambient temperatures >32 °C and RH > 60 % are considered as hot and humid environments (He, 2000; Zhao et al., 2009). These results suggest that the higher thermal resistance of PPE exposed the participants to both hotter and more humid environments, thereby increasing their HR. Moreover, owing to the congestion caused by PPE, Heat exchange through radiation, convection, and evaporation between the subjects and the environment was significantly impaired. In addition, according to the guidelines cited in previous studies (Fanger, 1970; Greenleaf and Castle, 1972; Hardy et al., 1938; ISO 7933, 2004), the increase in HR (~12 bpm), MST (~1.5 °C), and T_{ac} (~1.1 °C) observed in this study indicated that PPE use increased the metabolic rate and heat storage in the subjects.

Moreover, on wearing PPE, subjects had exhibited an increase in MTSV, from 0.6 to 3.0; an increase in MHSV, from 0.2 to 1.5; and a decrease in MMSV, from 0.3 to −2.2. Overall, these changes which represented largely intolerable changes with regards to thermal environmental parameters (both Ta, RH, and Va). In addition, the linear and probit regression results indicated that subjects with PPE required relatively lower neutral, preferred, and acceptable temperatures than those without PPE. Before wearing PPE, the subjects required a neutral $T_{op}/WBGT$ of 29.2/26.9 °C, a preferred T_{op} of 28.4/26.8 °C, and an upper acceptable WBGT of 29.4 °C. However, when the subjects wore PPE, their neutral $T_{op}/WBGT$ decreased to 19.5/19.8 °C, and their preferred $T_{op}/WBGT$ was 26.2/22.8 °C, with an upper limit of acceptable WBGT of 20.6 °C when the unacceptability rate was 20 %. This could be because the high thermal resistance of PPE may have reduced the heat dissipated by the human body to the environment. Additionally, when wearing PPE, a larger temperature gradient should be compensated. Notably, previous studies (Yang et al., 2013; Yang et al., 2014) have also found a higher neutral temperature than the preferred temperature in outdoor urban spaces.

4.2. Effects of using PPE on the physical and physiological health of human

Previous investigations have shown that prolonged exposure to heat and high temperatures increases heat stress and health risks in workers across different industries (Borg et al., 2021; Cheung et al., 2016; Ebi et al., 2021; Gao et al., 2018; McCarthy et al., 2018; Varghese et al., 2018). To date, the COVD-19 pandemic has been closely associated with hot weather and heatwaves. Therefore, the physical and physiological health of HCWs, particularly those who wear PPE, requires further investigation, as wearing PPE can cause physical and psychological stress in people. Moreover, previous studies (Chughtai et al., 2019; Mao et al., 2022; Rebmann et al., 2013) have reported several symptoms of physical discomfort in subjects who wore PPE; consequently, there is increasing resistance to wearing PPE and the duration of PPE use. Additionally, sweating and headaches associated with wearing PPE have been reported to be serious risk factors (Lim et al., 2006; Lin et al., 2020; Ong et al., 2020; Tabah et al., 2020; Taylor et al., 2015). Therefore, the duration of PPE usage should be appropriately controlled and reduced.

Nevertheless, while wearing PPE, an increase in HR, RF, and $P_{ET}CO_2$, and a decrease in SpO_2 were observed. This indicated that due to PPE, the average HR of the subjects increased by 12 bpm, average RF increased by 5 bpm, average $P_{ET}CO_2$ increased by 0.45 kPa, and blood oxygen concentration decreased by 0.23 %.

The normal RF for adults is 12–20 bpm (Yuan et al., 2013), and the comfort HR is 60–95 bpm (Zheng et al., 2019). In this study, the mean HR and RF of the subjects while wearing PPE reached 18 bpm and 88 bpm, respectively, which although was within the normal range, it was high, and thus, HCWs should be alerted about the adverse health effects of wearing PPE regularly.

Normal SpO_2 (blood oxygen measured by pulse oximeters) in healthy individuals is usually in the range of 95–100 % (Elder et al., 2015; Hafen and Sharma, 2022). However, the mean SpO_2 concentration of the subjects with PPE was 98.34 %, which was within the normal range, but concentrations below 95 % were also observed. The decrease in SpO_2 at high temperatures may affect the intensity of some acutely healthy symptoms, such as increased fatigue (Lan et al., 2011). Low SpO_2 is also associated with decreased cognitive function, which is more pronounced at high temperatures (Andersson et al., 2002; Lan et al., 2011; Winder and Borrill, 1998). Other studies have also confirmed that PPE use reduces SpO_2 in HCWs (Choudhury et al., 2020; Doğan et al., 2022; Moshtaghi-Kashanian et al., 2021).

Furthermore, normal $P_{ET}CO_2$ values generally range from 4.6 to 6.0 kpa (Thomas, 1981). In this study, the observed $P_{ET}CO_2$ ranged from 3.2 to 6.2 kpa, with average values of 4.4, 4.9, and 4.6 kpa for Phases 1, 2, and 3, respectively. These results indicate that $P_{ET}CO_2$ (indicating a higher arterial CO_2 level) was higher with PPE than without PPE, and the same trends were observed for HR and RF. Furthermore, $P_{ET}CO_2$ increases have been observed both when wearing masks (Bharatendu et al., 2020; Law et al., 2021; Scholkmann et al., 2021) and at high temperatures (Fan et al., 2019; Lan et al., 2011; Liu et al., 2017). More importantly, energy consumption increases under hot conditions because more energy is needed by the body to transfer excess heat from core tissues, which increases the cardiac load and HR, and because warmer tissues have a high metabolism rate (Burton and Edholm, 1955; Ebi et al., 2021). A corresponding increase in the metabolic rate has been reported owing to an increase in temperature (Cannon and Keatinge, 1960; Gagge et al., 1967). As expected, this result indicates that, as the body becomes hot, the rate of heat production increases owing to an increase in the rate of chemical reactions within the body cells (ISO 7933, 2004). Moreover, the increase in T_{ac} (by approximately 1.2 °C) and MST (by approximately 1.5 °C) of the subjects while wearing PPE reflects an increase in the core and body temperatures.

The normal range of core temperature is 36.5–37.5 °C and that during fever is 36.5–38.3 °C (Garner and Fendius, 2010). However, the average T_{ac} of subjects with PPE reached 37.2 °C. Although Yan et al. (2005) reported a comfortable Tac range of 35.5–37.4 °C, the applicability of our conclusion can be confirmed from the results of the subjective sensation evaluation and is perhaps still debatable. Moreover, MST reached 35.4 °C in subjects who wore PPE, and this value was beyond the range of comfortable skin temperatures reported by Li (2012).

Furthermore, the responses to physiological indicators and physical symptoms experienced by the subjects wearing PPE indicated that they experienced impaired health and performance. Thus, it is necessary to develop appropriate strategies to minimize the risk to HCWs in parallel with the implementation of anti-COVID-19 measures. Generally, these strategies include three main areas. First, create shaded workplaces and rest areas for the workers. When performing nucleic acid sample collection outdoors, it is recommended to perform it under overhead (semi-open transition space) rather than under a temporary shade shelter. However, working in PPE exposed to outdoor solar radiation is not desirable. Second, worker-applicable interventions should be developed, including locally adapted heat stress risk warning systems and heat stress mitigation measures. Studies (Petersson et al., 2019; Morabito et al., 2019) have been conducted to develop locally appropriate thermal warning systems and systems that use climate services to translate personalized warning and adaptation strategies. The important reference roles of thermal neutral temperature, preferred temperature, and acceptable temperature derived from this study in the development of locally appropriate thermal warning systems for survey sites are acknowledged. On the one hand, previous studies (Maté et al., 2016; Watkins et al., 2018) have reported that ice slurry ingestion can lower core body temperature before and during activity, which can reduce heat stress in workers. For healthcare workers in the medical sector wearing PPE, ice slurry ingestion has been shown to be practical and effective in improving thermal comfort (Lee et al., 2020). On the other hand, the worker's work schedule and work intensity are also the focus of interventions. One strategy is to reduce the intensity of physical work and increase the frequency and length of rest periods to reduce heat production in the body. For example, scheduling the most physically demanding or longest-lasting tasks to the coolest time of day, promoting hydration even outside of shifts, and before feeling thirst. Third, the use of cooling (cooling vest) and ventilation techniques (ventilated clothing) to reduce the heat stress and improve the thermal comfort of workers is perhaps the most direct and effective strategy. The use of cooling vests to reduce thermal strain or improve thermal comfort in hot environments is an effective adaptation measure (Gao, 2014; Hamdan et al., 2016; Itani et al., 2017). Moreover, studies have claimed that a novel personal cooling system incorporating phase change materials and ventilation fans may be a more effective means of combating heat-stress symptoms in both hot and humid environments (Lu et al., 2015). Zhao et al. (2017) found that the cooling capacity of new anti-heat stress clothing ensembles could help workers recover from heat stress faster and be more conducive to developing work break schedules. Nevertheless, the use of a single aspect of the anti-heat stress strategy cannot be considered the most appropriate or optimal, and multiple dimensions should be considered when developing appropriate and effective strategies.

4.3. Limitation and future work

This study focused on the physiological responses and thermal comfort of HCWs wearing PPE. However, it has a couple of limitations. Occasionally, nucleic acid samples are collected indoors or outdoors in shaded environments; further work considering different environmental conditions should be conducted. PPE is used in various seasons as well as in various scenarios, such as when caring for patients in reception rooms and surgical rooms and while working in the ICU. Thus, more studies on PPE use in other situations and seasons should be conducted in the future. Furthermore, this study only examined the changes in young college students, who did not have better tolerance, including heat tolerance and tolerance of physiological symptoms, should be no better than those of workers who regularly wear PPE in the medical sector; people of different age groups and different tolerances should be considered, and their responses should be analyzed in future research. The microenvironment between the human body and PPE, especially masks, faces, heads, and coveralls, should be studied more comprehensively in the future (e.g., using heat transfer modeling). The increased metabolic rate and heat storage of the subjects while wearing PPE were estimated based on their T_{ac} and HR, according to Greenleaf and Castle (1972), Hardy et al. (1938), and ISO 8996 (2004). However, in future studies, the current observations can be validated using direct measurements of metabolic rate, as cited in ISO 8996 (2004). It is important to note that for HCWs who wear PPE to work under hot conditions, more attention should be paid to the evaluation of heat stress in future studies. For example, a more detailed heat stress index-predicted heat strain (PHS) in ISO 7243 (2017) was used to assess the heat stress conditions they experienced. Further, the existing PHS and WBGT should be revised and improved according to the guidelines of BS 7963 (2000) to assess, to the extent possible, the possible effects of heat stress on workers who must wear protective clothing or other PPE that may affect their personal thermal environment.

5. Conclusions

In September 2021, an experiment and questionnaire were conducted in the half-open transitional space in Guangzhou to explore the thermal stress of subjects with and without PPE during nucleic acid sample collection in the semi-open transition space, and the thermal environment parameters were logged. The following results were obtained:

(1) Thermal comfort differed significantly with and without PPE. As subjects wore PPE, they had MTSV, MHSV, and MMSV of 3.0, 1.5,

and − 2.2, respectively, compared to 0.6, 0.2, and 0.3, respectively, when they did not wear PPE. Consequently, most of the subjects felt unacceptable, and thus, a relatively lower temperature, RH, and stronger airflow were desirable for ensuring thermal comfort and mitigating thermal stress.

(2) T_{ac}, MST, HR, RF, and $P_{ET}CO_2$ increased significantly, whereas SpO_2 decreased significantly in subjects who wore PPE. The physiological responses of these subjects suggested that their health conditions were compromised and that they showed high core temperature, high metabolic rate, increased heat storage, increased fatigue, respiratory-related illness, and cognitive impairment. Thus, controlling and managing the time required to use PPE is essential.

(3) In general, subjects who wore PPE required much lower neutral, preferred, and acceptable temperatures than did those who did not wear PPE. Moreover, the results of linear regression and probity regression analysis indicated that the neutral $T_{op}/WBGT$ was 29.2/26.9 °C before wearing PPE and 19.5/19.8 °C with PPE. Additionally, the preferred $T_{op}/WBGT$ was 28.4/26.8 °C before wearing PPE, whereas it was 26.2/22.8 °C while wearing PPE. Moreover, a lower upper acceptable WBGT limit of 20.4 °C was obtained while wearing PPE (29.4 °C before wearing PPE). In conclusion, the need for such temperature changes indicated that subjects wearing PPE require a cooler thermal environment to maintain heat balance and thermal comfort.

CRediT authorship contribution statement

Zhaosong Fang: Conceptualization, Supervision, Methodology, English editing.

Yudong Mao: Methodology, Data curation, Writing- Original draft preparation,

Yongcheng Zhu: Conceptualization, Methodology, Data curation, Resource.

Jiaxin Lu: Methodology, Data curation.

Zhimin Zheng: Conceptualization, Writing- Reviewing.

Xiaohui Chen: Conceptualization, Resource, Validation.

Zhaosong Fang, Yudong Mao and Yongcheng Zhu have contributed equally to this article.

Data availability

The authors do not have permission to share data.

Declaration of competing interest

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

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Appendix A. Thermal comfort survey questionnaire field experiments for nucleic acid sample collection

It takes approximately 3–5 min to complete the anonymous and confidential questionnaire, which does not include correct or incorrect answers, but only answers that reflect your personal views and experiences. The completeness of the answers is critical to the validity of the study. Thank you for participating in this field experiments.

Participation No._____ Age_____ Sex____ Height_____ Weight_____

Date: / / Time: : am/pm.

Section I

Part 1: Your current experimental phase

Phase1: Before wearing PPE **Phase2:** Wearing PPE **Phase3:** After removing PPE.

Part 2: Subjective sensation evaluation

2.1 Evaluation of thermal sensation (How does the thermal sensation feel to you now?)

☐ -4 Very cold ☐ -3 Cold ☐ -2 Cool ☐ -1 slightly cool ☐ 0 Neutral ☐ 1 slightly warm ☐ 2warm ☐ 3 hot ☐ 4 very hot☐

2.2 Evaluation of humid sensation

☐ -4 extremely dry ☐ -3 very dry ☐ -2 dry ☐ -1 slightly dry ☐ 0 neutral ☐ 1 slightly humid ☐ 2 humid ☐ 3 very humid ☐ 4 extremely humid.

2.3 Evaluation of air movement sensation

☐ -3, very weak ☐ -2, weak ☐ -1, slightly weak ☐, neutral ☐ 1, slightly strong ☐ 2, strong ☐ 3, very stron

Section II

Part 3: Evaluation of the acceptability for thermal environment parameters

Overall evaluation of environmental parameters (What do you think of the current environmental parameters?)

 Ambient temperature

☐ Acceptable (−1) ☐ Unacceptable (1)

 Ambient relative humidity

☐ Acceptable (−1) ☐ Unacceptable (1)

 Ambient air velocity

☐ Acceptable (−1) ☐ Unacceptable (1)

Part 4: Evaluation of the preference for thermal environment parameters

Preference for environmental parameters (How do you expect environmental parameters to change?)

 Expectations of ambient temperature

☐ lower (−1) ☐ no change (0) ☐ higher (1)

 Expectations of ambient relative humidity

☐ lower (−1) ☐ no change (0) ☐ higher (1)

 Expectations of ambient air velocity

☐ lower (−1) ☐ no change (0) ☐ higher (1)

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