The distorted power of medical surgical masks for changing the human thermal psychology of indoor personnel in summer

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Abstract

The medical surgical mask (MSM) has been the essential protective equipment in people’s daily work. The experimental purpose is to explore the effects of wearing MSM on human thermal sensation, thermal comfort, and breathing comfort in office buildings in summer. A total of 30 healthy college students were recruited for the testing. The experiment was carried out in a climate chamber, which can simulate the office buildings in summer. The experiment collects the subjects’ skin temperature, microclimate in the mask, and subjective votes, including thermal sensory votes (TSV), thermal comfort votes (TCV), and respiratory comfort votes (BCV). Experimental results show that wearing MSM has no significant effect on the skin temperature of the human body. The microclimate temperature inside the MSM reaches over 34°C, and the relative humidity reaches over 70%. The high-temperature and high-humidity microclimate put human beings in an uneven thermal environment, which leads to poor human tolerance to the thermal environment and becomes the main reason for destroying human thermal comfort. Wearing MSM has a significant impact on the subjective thermal sensation, thermal comfort, and breathing comfort of the human body, and the impact becomes more significant as the environmental temperature increases. Once the mask is taken off, the human body will enter an extremely comfortable environment, resulting in an excessively high vote value. The difference in voting values before and after removing the mask becomes larger with the environmental temperature. By fitting the voting results and perform data processing, it can be found that wearing MSM will reduce the neutral temperature by 1.5°C, and the environmental temperature with the optimal thermal comfort by 1.4°C, and as the temperature increases, the respiratory discomfort will become more and more intense. Regardless of whether wearing a MSM, the subjects preferred a slight warmer environment. In conclusion, with the increase of ambient temperature, wearing MSM can cause the human worse tolerance to the thermal environment, and this disturbance will become more and more intense.

KEYWORDS
breathing comfort, environmental temperature, medical surgical masks, thermal comfort, thermal sensation
1 | INTRODUCTION

The thermal comfort and thermal adaptation of the occupants have always been hot spots in the environment and building science.\(^1\)\(^-\)\(^5\) As public health problems continue to ferment, people have been paying more and more attention to the prevention of respiratory diseases, especially now that the COVID-19 is spreading worldwide. The WHO proposed\(^6\) that wearing MSM is an effective measure to prevent the transmission of COVID-19 and other certain respiratory viral diseases in airless spaces. However, the airflow in the head area will have a huge impact on thermal comfort in a neutral thermal environment.\(^7\)\(^,\)\(^8\) The MSM has high-quality filtering performance and good facial fit, so the breathing heat accumulated inside the mask will produce a hot and humid microclimate.\(^9\) There are significant differences in the temperature and humidity of the microclimate and environmental air.\(^10\)\(^,\)\(^11\) And the microclimate in the mask will seriously affect the human thermal sensation and thermal comfort.\(^11\) It is equivalent to applying local thermal stimulation to the sensitive skin surface around the mouth, nose, and cheeks, which will further affect the human thermal sensation and comfort. The related studies have also shown that the local discomfort of a single body part usually determines the overall thermal comfort.\(^12\)\(^,\)\(^13\) Zhang et al.\(^14\) considered that human thermal comfort is a function of local and whole body thermal sensations. Pellerin et al.\(^15\) found that there is an important relationship between the number of uncomfortable local body parts and thermal comfort or thermal satisfaction, and more than 70% of the subjects will feel discomfort or dissatisfaction when more than two body parts are uncomfortable. An uncomfortable thermal environment will not only disturb the human comfort, but also decrease the crew working efficiency,\(^16\)-18 especially in the hot summer environment.\(^19\)-21

The thermal comfort evaluation usually determines the thermal insulation value of functional clothing to estimate the thermal load.\(^21\)-23 However, the MSM is different from conventional clothing, and it can hinder the human breathing and heat dissipation. The thermal difference between microclimate and environmental will cause significant changes in physiological activities and metabolic levels required to adapt to the environment. The traditional average voting model (ISO-7730\(^24\)) or thermal strain model (ISO-7933\(^25\)) estimates breathing heat by convection and evaporation. The heat insulation of MSM greatly reduces the breathing heat dissipation, and most of the breathing heat becomes the driving force for maintaining the microclimate.\(^26\) Compared with the expected level when not wearing MSM, the hot and humid microclimate will create an additional thermal physiological burden, which can severely impact the thermal sensation.

Wearing MSM will create a non-uniform environment with local thermal stimulation. To quantify the comfort improvement effect of local adjustment equipment, Zhang et al.\(^27\) once introduced the term "corrected power (CP)," which refers to the ability of the device can "corrects" a "warm" or "cool" environmental temperature toward neutral, and the unit is °C. Luo et al.\(^28\) found the CP of local heating/cooling equipment is 3.6–6.5°C, even the combination of these devices can make more than 80% people accept an environmental temperature of 18 or 29°C. The microclimate inside the mask also causes deviations in thermal sensation and thermal comfort, which can regard as the "distorted power" of medical surgical masks for the thermal environment.

In the past two decades, the effects of wearing a respirator or MSM on thermal physiology have been studied on different topics. Roberge et al.\(^15\) studied the effects of wearing MSM on heart rate, breathing rate, skin temperature, fatigue, and thermal sensation. The microclimates in N95 or MSM have significantly different temperatures and humidity, which has a profound effect on heart rate, heat stress, and subjective discomfort.\(^29\) Guo\(^30\) then studied the effects of masks with exhaust valves or exhaust holes on human physiological parameters. Kim\(^31\) studied the suitability of filter mask respirators (FFR) in hot and humid environments. Lin\(^26\) studied the changes of body temperature and heat sensation after wearing tight-fitting respirators and exercising in a hot and humid indoor environment. Recently, affected by the COVID-19 epidemic, some researchers have also studied the filtration performance of masks with different functions and materials.\(^32\)-33 The above studies are still carried out in a single thermal environment, such as hospitals. The masks involved are more focused on the highly airtight N95, valve masks, and the core content is the impact of mask performance on physiological parameters and human comfort. But the impact of the correlation between the environment and MSM on human thermal comfort is not involved.

With the frequent occurrence of public health problems, it will be normal that wearing MSM indoors for long periods of time. The paper analyzes the changes of the human thermal adaptability in different summer indoor environments, and the deviation of the neutral thermal environment when crew wearing MSM. The experiment utilized a climate chamber to build a highly uniform thermal environment to imitate the working environment in summer. By collecting subjects’ physiological data and subjective perception voting, the
effects of local thermal stimulation caused by MSM on the human thermal psychology under different indoor thermal conditions are evaluated, and the “distorted power” of MSM for environmental temperature is explored.

2 | EXPERIMENT

2.1 | Experimental location

The experiment was performed in the climate chamber (4 m × 4 m × 3 m) in University of Shanghai for Science and Technology. The internal and external environment of the climate chamber is separated by a 120 mm thick wall, which is composed of layer steel plate and the insulating polyurethane filler. Before the air is fed to the room, it will be treated by a refrigeration unit, an air handling unit, heaters, and humidifier. The refrigerator provides the rated refrigerating capacity through the ethylene glycol as second refrigerant so as to perform the rough temperature adjustment. And then, the electric heater in the air handling unit provides the variable heating capacity through PID control so as to perform the refined adjustment to temperature and enable the air temperature to reach the setup value. Finally, the humidity is adjusted through the humidifier. Air is supplied through the ceiling vent and returns through a vent in the lower wall. The ventilation rate is 60 times per hour. The indoor temperature can be adjusted within the scope of −5 to 45°C with the precision of ±0.30°C. The relative humidity can be controlled within the scope of 10–90% with the precision of ±5%. It is able to control the air velocity within the scope of 0.1–2 m/s with the precision of ±0.3/s. Figure 1 is the physical image for the climate chamber. The room uses LED lights for office use (correlated color temperature is about 4000 K), and the lighting level is 300 lux.

2.2 | Subject

There are 30 subjects participated in this experiment, including 15 males and 15 females, each of them participated in the experiment under all working conditions. The subjects’ previous thermal experience may affect thermal comfort preferences, such as the climate of the hometown and the residence time in Shanghai. Therefore, the subjects are all volunteers who have lived in Shanghai for more than two years, and their hometown is not an extremely cold or hot area. The subjects’ physical conditions are shown in Table 1. Taking into account the age and exercise of the staff in an office building, the subjects are all young healthy college students engaged in sedentary activities, and they may not be as sensitive to the thermal environment as other groups (the elderly, patients, etc.). The experiment required the subjects to have a balanced diet, maintain adequate sleep, and do not drink or drugs within 24 hours before participating in the experiment. The experiment required subjects to wear collarless T-shirts and trousers with the same material (insulation level 0.5). The subjects with long hair were required to tie their hair up, which helps to minimize variables that may affect comparable results.

During the experiment, all subjects understood the purpose and significance of the experiment, but they were not informed of environmental parameters to avoid affecting subjective judgment. All subjects were told that they could withdraw from the study without prejudice at any time.

2.3 | Medical surgical masks

According to the requirements of the WHO, all subjects must wear MSM correctly during the experiment. The physical picture and size of the mask are shown in Figure 2. According to the standards provided by the manufacturer, the inhalation resistance of the MSM is <49 Pa, the exhalation resistance is <29.4 Pa, and the filtering efficiency for non-oily particles is <30%. The MSM has a three-layer structure, the inner layer is made of skin-friendly material (ordinary sanitary gauze or non-woven fabric), the middle layer is an isolation filter layer (ultra-fine polypropylene fiber melt-blown material layer), and the outer layer is made of special material bacteria layer (non-woven fabric or ultra-thin polypropylene melt-blown material layer). The related research showed that the effectiveness of MSM in blocking the spread of microorganisms is three times that of cotton masks.
2.4 | Parameter measurement

The experiment collected the subject’s skin temperature and the microclimate parameters in the MSM.

2.4.1 | Skin temperature measurement

In order to clearly observe the effect of microclimate on skin temperature, the skin temperature of the face and other parts was collected. The layout of the test points of the subject’s skin temperature is shown in Figure 3A, including the nose, posterior neck, chest, forehead, left leg, and left arm. The actual test layout is shown in Figure 3B. The experiment used Agilent data acquisition instrument to collect temperature every 10 s and utilized thin film platinum resistance PT1000 (Omega, 0–50°C, ±0.15°C) for the skin temperature measurement, which has high measurement accuracy and is easy to fix and measure. In the experiment, the medical tape was used to fix it on the predetermined position of the human skin. The measurement points should be placed far away from the joints of the body. This is because there are no muscles and fats around the joints, and metabolism is much lower than the average level of the human body. The skin temperature regulation ability of the joints is limited at lower or higher environmental temperature.

2.4.2 | Microclimate parameters

In order to analyze the local thermal stimulation caused by the microclimate, the probe-type temperature and humidity sensor was used to collect the microclimate in the mask. For the temperature and humidity measurement sensor, the temperature accuracy is ±0.0625°C, the humidity accuracy is ±2.0%, and the temperature probe is DS18B20.

2.5 | Indoor thermal environment measurement

In the experiment, the main indoor climate parameters were measured, including air temperature, relative humidity, radiant temperature, air velocity, and vertical temperature difference. These parameters were measured at a height of 1.1 m above the ground. The mean radiant temperature was measured through the measurement of globe temperature using black globe thermometer, which is one of the three measurement methods for the mean radiant temperature listed in ISO standard 7726. The average radiation temperature was calculated based on the measured air temperature, globe temperature, and air velocity. To avoid the local discomfort caused by the vertical air temperature difference, the air

| Gender | Amount | Age  (±) | Height (m)  (±) | Weight (kg)  (±) |
|--------|--------|---------|----------------|-----------------|
| Female | 15     | 25 ± 1.6| 1.63 ± 0.06    | 53.9 ± 7.6      |
| Male   | 15     | 25 ± 1.4| 1.75 ± 0.03    | 67.4 ± 6.0      |
| Average| 30     | 25 ± 1.5| 1.69 ± 0.05    | 60.7 ± 8.3      |

FIGURE 2 The actual size and three-layer structure of the MSM

FIGURE 3 Schematic diagram of human body temperature measurement layout—(A) The layout of the test points of the subject’s skin temperature. (B) Actual test layout
temperature at heights of 0.1, 1.1, 1.7, and 2.8 m was measured.\(^{22}\) The main measuring instruments used in the experiment are shown in Table 2.

### 2.6 Experimental process

During the experiment, the environmental temperature was maintained at 22–28°C, which was divided into 7 working conditions, and the temperature interval between adjacent working conditions was 1°C. The air relative humidity in the experiment chamber was stable at 50%. In order to reduce the impact of blowing sensation on human comfort, the indoor air velocity was <0.1 m/s.\(^{22,24}\) The experimental conditions are shown in Table 3. In each experiment, 1 subject is tested in the climate chamber.

The duration of each working condition was 1.5 h, which is divided into three stages: the adaptation stage (0.5 h), the MSM-wearing stage (0.5 h), and the MSM-removing stage (0.5 h). During the whole experiment, the environmental temperature remained constant. They can read or work (1.0 met, 1 met = 58.2 W/m\(^2\)) and perform normal conversations or physical movements, which simulates the daily work of staff in the office. During the experiment, the subjects were asked to avoid negative emotions,\(^{40}\) and drink or eat nothing. In the last 5 min of the adaptation phase, the subjects filled out questionnaires about thermal sensation, thermal comfort, and breathing comfort. In the MSM-wearing stage (0.5 h), the subjects filled in the questionnaires every 2 min in the first 10 min, and every 4 min in the last 20 min. For the MSM-removing stage (0.5 h) that the environmental parameters remain unchanged, the subjects gradually adapted to the original environment and filled out three questionnaires every 2 min. The thermal sensation vote used ASHRAE’s 7-point method, and the thermal comfort vote and breathing comfort vote used the same intermediate fracture continuous scale, which are shown in Figure 4. Breathing comfort refers to whether the subjects breathe smoothly, regardless of the facial fit and ears comfort.

### 2.7 Statistical analysis

The statistical analysis is performed using average values calculated based on subjects’ experimental data. The SPSS 22 is used to test the significant difference. It is considered to exist difference (*) when \(p < 0.05\), and it is considered to exist significant difference (**) when \(p < 0.01\).

### 3 ANALYSIS OF EXPERIMENTAL RESULTS

#### 3.1 Skin temperature of various parts

As the test time increases, the local skin temperature reaches a steady state. Figure 5 shows the steady skin temperature of various parts at different environmental temperature. The subjects have been in a steady-state environment, so the temperature of the remaining parts is stable except for the nose affected by microclimate. With the decrease of the steady-state environmental temperature, due to the different metabolic levels of various parts of the human body, the local temperature has decreased to varying degrees. The posterior neck, chest, and forehead are in the core area of body, and the temperature of these places is relatively consistent. The left leg and left arm are far from the core of the torso, and the temperature is lower. The nose temperature is slightly higher than other positions, and it shows a rising trend with the increase of testing time. Besides, the temperature of core parts has small changes, such as the head, while the arms, legs, and feet have large changes, which is consistent with the result of Liu.\(^{41}\) The legs and hands are far from the heart, and the cell metabolism level is lower than that of the trunk core. Therefore, the legs and hands are greatly affected by the environmental temperature and have poor temperature regulation. The cell metabolism of the head and chest is very active, and the skin temperature changes very little.

#### 3.2 Microclimate

As the test time increases, the microclimate parameters reach a steady state. Figure 6 shows the steady microclimate parameters at different environmental temperature. The microclimate temperature reaches over 34°C, and the relative humidity reaches over 70%. Affected by the increase of environmental temperature, the temperature and relative humidity of the microclimate show a small increase. Compared with the external thermal environment, the microclimate temperature and relative humidity are very high.

| Test items        | Instrument       | Model      | Test range | Precision   |
|-------------------|------------------|------------|------------|-------------|
| Air temperature   | PT1000           | Omega      | 0–50°C     | ±0.15°C     |
| Relative humidity | Humidity sensor  | Testo625   | 0%–100%    | ±2.5%       |
| Air velocity      | Thermal sensitive anemometer | Testo425 | 0–20 m/s   | ±0.01 m/s   |
| Globe temperature | Thermometer      | AZ87783    | 0–50°C     | ±0.6°C      |
| Data collection   | Data collector   | Agilent    | /          | /           |
3.3 | Thermal sensation vote (TSV)

Figure 7 shows the variation trend of TSV with the testing time at different environmental temperature. From the experimental results, wearing MSM will significantly change the whole body’s thermal sensation. As the testing time increases, the subjects who wearing MSM feel hotter, and the TSV gradually increases and reaches a steady state after a period of time. The reason is that the coverage of MSM increases the difficulty of heat dissipation of the human body. The local thermal stimulation caused by microclimate can make the subjective thermal sensation rise. Constantly inhaling high-temperature and high-humidity air can hinder breathing evaporative heat dissipation and breathing convective heat dissipation, which can aggravate the thermal sensation worse. When the MSM is taken off, the temperature of the facial skin drops rapidly due to the facial skin is directly exposed to the environment, and the cool ambient air is continuously inhaled, so the thermal sensation will be greatly reduced. With the gradual adaptation to the environment, the thermal sensation decreases rapidly until it reaches stable. In the paper, the steady TSV refers to the TSV that reaches a stable or normal level, which is also used for TCV and BCV.

As the environmental temperature increases, the steady TSV will continue to increase. This is the inevitable trend of the human body’s physiological response. However, wearing MSM has different effects on the thermal sensation in different temperature ranges.

When the environment is 22, 23, and 24°C, the steady TSV increases as the temperature rises, which is −2.0, −1.2, and −0.4 in turn. Moreover, as the environmental temperature increases, the time for TSV to reach a steady state becomes shorter and shorter. The increase of environmental temperature also has a significant impact on the steady TSV difference before and after removing MSM. At the 22–24°C environmental temperature, the effect of wearing MSM on the human body’s thermal sensation is not obvious, and the maximum steady TSV difference before and after removing the MSM is about 0.4. This is because other body parts are exposed to the low-temperature environment, the mean skin temperature will decrease, and the subjects feel cool or even cold. At this time, the human body has a small amount of heat dissipation, so wearing MSM has little effect on the thermal sensation, and even it can effectively relieve the human body’s cold sensation. Once the environmental temperature rises, the TSV with wearing MSM will increase significantly. When the environmental temperature is 28°C, the steady TSV is 2.3, and the steady TSV difference before and after removing the MSM is about 1.7, it indicates the MSM has a significant influence on the human body’s thermal sensation. The thermal sensation originally increases with the increase of environmental temperature, and wearing MSM can cause subjects to be hotter and a sharp increase

### TABLE 3 Experimental conditions

| No. | t, °C | Δt, °C/m | RH, % | v, m/s |
|-----|-------|----------|-------|-------|
| 1   | 22.1  | 0.11     | 50.7  | 0.06  |
| 2   | 23.1  | 0.10     | 50.3  | 0.08  |
| 3   | 24.0  | 0.12     | 50.6  | 0.07  |
| 4   | 24.9  | 0.13     | 50.9  | 0.08  |
| 5   | 26.0  | 0.09     | 49.8  | 0.08  |
| 6   | 27.1  | 0.08     | 50.6  | 0.07  |
| 7   | 28.1  | 0.11     | 50.6  | 0.08  |

Figure 4 Voting questionnaire

Figure 5 Average skin temperature of body parts
of TSV. The above changes indicate that the higher environmental temperature, the more significant impact of wearing MSM on the human thermal sensation. In a hot environment, it is more difficult for the human skin to dissipate heat, and wearing MSM effectively hinders the breathing heat dissipation, forcing TSV to rise.

3.4 | Thermal comfort vote (TCV)

Figure 8 shows the variation trend of TCV with test time at different environmental temperatures. The TCV at all experimental conditions is all less than 0, which indicates that wearing MSM will make subjects feel thermal discomfort. With the time of wearing the mask increases, the subject’s TCV will decrease and reach stability. The changes of environmental temperature will also affect the steady TCV. When the environmental temperature is 22–25°C, the TCV increases with the increase of environmental temperature, and the TCV is −2.1, −1.3, −1.0, and −0.6 in turn. When the environmental temperature is 25–28°C, the TCV decreases with the increase of the environmental temperature, and the TCV is −0.9, −1.4, and −1.9 in sequence. The opposite trend indicates that there is an environmental temperature that can ensure the optimal thermal comfort when wearing MSM.

After taking off the MSM, the subjects quickly entered into a very comfortable state. Fresh air enters the body directly through the respiratory tract, and the cooling capacity will greatly increase, resulting in a rapid improvement of thermal comfort. After enduring up to 30 min of thermal discomfort, once the MSM is removed, the comfort at this time is in obvious contrast with the strong discomfort when wearing MSM, resulting TCV after removing the MSM will increase first. The phenomenon can also be observed in the TSV changes in Figure 7.

In addition, the time for TCV to reach steady state becomes shorter and shorter with the increase of environmental temperature. In an environment of 22–24°C, wearing MSM do not cause a significant change in thermal comfort, even there is no obvious effect at 22°C. However, the TCV will quickly decrease to a steady state when the temperature is higher than 24°C, and the reduction is as high as 2.7 at 28°C. In addition, the steady TCV difference before and after removing the MSM is getting higher with the environmental
temperature increases. The maximum steady TCV difference is 0.3 at 22–24°C, but it even increases to 3.4 at 28°C. The above changes indicate that the increase of environmental temperature will aggravate the impact of wearing a mask on thermal comfort. This is because that the subjects feel cold in a low-temperature environment, and the human body has a small amount of heat dissipation, which weakens the impact of MSM on thermal comfort.

3.5 Breathing comfort vote (BCV)

Figure 9 shows the variation trend of BCV with testing time at different environmental temperatures. As the time of wearing MSM increases, the subjects’ breathing comfort will gradually deteriorate and then stabilize. The MSM has excellent filtering performance, which is also at the expense of air permeability. Wearing MSM can form a high-temperature and humidity microclimate and increase the respiratory resistance, resulting in the decrease of breathing comfort. From the experimental results, this discomfort becomes more and more intense as the environmental temperature increases. When the environmental temperature rises from 22 to 28°C, the steady BCV decreased from –0.8 to –2.4. For the indoor staff wearing MSM, the appropriate reduction of environmental temperature can improve breathing comfort. After taking off the MSM, breathing comfort will quickly return to normal levels. The stronger the breathing discomfort while wearing the MSM, the more comfortable the subjects felt after removing the MSM.

With the environmental temperature increases, the BCV decrease rate when wearing MSM is getting faster, and the BCV decrease rate at 28°C is 2.2 times that at 22°C. In addition, as the environmental temperature increases, the steady BCV difference before and after removing MSM also increases. At 22°C, the steady TCV difference is 1.3, and the steady TCV difference increases to 2.6 at 28°C. It means that the increase of the environmental temperature can enhance the disturbance of wearing a MSM to breathing comfort. As the environmental temperature rises, the breathing rate gradually increases to dissipate the metabolic heat in time. Wearing MSM can increase the breathing resistance, causing fresh cool air to not enter the human body in time for heat exchange, so the BCV drops sharply.

4 DISCUSSION

4.1 Skin temperature and microclimate in the mask

The experiment was carried out in a uniform and stable thermal environment, and the skin temperature of the nose inside the mask was collected. With the increase of environmental temperature, the nose skin temperature did not change significantly ($p = 0.35$). Compared with the legs or arms, the effect of environmental temperature on nose is much less. Because the nose is covered by a MSM, the skin temperature of the nose is less affected by the external environment.

In fact, the microclimate in the MSM makes the human in a non-uniform thermal environment, which leads to the poorer human tolerance to the thermal environment, and it is the main reason for destroying the human thermal comfort. The microclimate relative humidity is as high as 70%, and the temperature is above 34°C. The microclimate with high temperature and humidity can seriously affect the breathing evaporative heat dissipation and the breathing convective heat dissipation. In order to enhance the heat dissipation of the human body, the human body enhances the heat dissipation by expanding the blood vessels of the skin, enhancing blood circulation, and sweating. Moreover, wearing MSM causes the corresponding decrease of the oxygen inhaled, so human need to deeper and faster breathing, which is manifested in the increase of lung ventilation. The above-mentioned human reaction is the primary cause of the destruction of human tolerance.

4.2 Environmental temperature and TSV

Figure 10 shows the relationship between environmental temperature and the steady TSV. In Figure 10A, regardless of whether the MSM is worn or not, the TSV will continue to increase with the environmental temperature increases. In a stable environment where humidity, air velocity, activity level, and thermal resistance are strictly controlled, the thermal sensation has a linear relationship with the environmental temperature. As the environmental temperature increases, it can be seen that wearing MSM has an increasingly significant impact on the human thermal sensation. The relationship between the steady TSV and the environmental temperature is fitted, and the linear relationship obtained is shown in Figure 10B. The fitting results show that the rising rate of TSV with the MSM increases 0.5 times than that without the MSM, and the neutral temperature make subjects embrace neutral thermal sensation is 24.6°C. When the MSM is not worn, the neutral temperature is 26.1°C. This means that wearing MSM causes the neutral temperature to reduce by about 1.5°C. So it can be considered the "distorted power" of the MSM can be considered –1.5°C.
In order to make the calculation results more credible, based on the measured TSV, the neutral temperature range is calculated by Griffiths correlation, as shown in Eq. 1. The neutral temperature range is 25.5–26.5 °C without the MSM, and it drops to 23.3–24.6 °C when wearing the MSM, which shows that wearing MSM can cause the neutral temperature to drop by 1.9–2.2 °C. The result is consistent with the calculated results from the fitted curve, and it also has a guiding significance for temperature adjustment in the office environment.

\[
t_{\text{neutral}} = t_0 - \frac{\text{TSV}}{G}
\]  

where \( t_{\text{neutral}} \) is the neutral temperature, °C; \( t_0 \) is the environmental temperature, °C; \( G \) is the Griffiths constant, and it is 0.5 according to.\(^{47}\)

### 4.3 Environmental temperature and thermal comfort

Figure 11 is the relationship between the environmental temperature and the steady TCV. It can be seen from Figure 11A that as the environmental temperature increases, the steady TCV presents a hump-shaped curve regardless of whether the MSM is worn or not. Too high or too low environmental temperature will destroy the human thermal comfort. By fitting the hump-shaped curve to a quadratic equation of environmental temperature, the environmental temperature with the steady TCV peak is determined, as shown in Figure 11B. According to the fitting results, when the MSM is not worn, the environmental temperature with optimal TCV is 26.3°C, and the optimal TCV is as high as 1.6, which means the crew feels comfortable. When the MSM is worn, the environmental temperature with optimal TCV is 24.9°C, and the optimal TCV is −0.8, which means the thermal comfort is between neutral and a little uncomfortable. Wearing MSM can cause the most comfortable environmental temperature to decrease by 1.4°C. Based on the experimental results, for workers who wear collarless T-shirts and trousers (\( \text{clo} = 0.5 \)) and sit in a normal indoor environment in summer with \( t \geq 26^\circ \text{C} \), wearing MSM will cause very serious disturbance. As the environmental temperature rises, this disturbance will be further reinforced. Decreasing the environmental temperature will reduce the wearer’s thermal discomfort as much as possible, but the thermal comfort is still below the neutral level, and this method also undoubtedly greatly increases the energy consumption of air conditioning in office buildings in summer.\(^{48}\)

### 4.4 Environmental temperature and breathing comfort

Figure 12 is the relationship between the environmental temperature and the steady BCV. Judging from the voting results in
Figure 12A, wearing MSM has a significant impact on the BCV. The relationship between the steady BCV and environmental temperature is fitted, as shown in Figure 12B. When the MSM is not worn, there is a hump-shaped curve between the environmental temperature and the steady BCV, and the steady BCV reaches the optimal in environmental temperature 26.1°C. Breathing is a way of adjusting heat dissipation for the human body. In a cold environment, the mean skin temperature of the human body is low, and the breathing volume and breathing rate are both small to reduce excessive human heat dissipation. However, in a hot environment, the breathing volume and the breathing rate are both increased to improve the heat dissipation.\(^{49}\) Besides, the respiratory tract is so sensitive to cold or hot air temperature that can also influence the breathing comfort. It indicates that the too high or too low temperature all will affect the body’s breathing comfort when the MSM is not worn. However, the fitting curve when wearing mask shows that the subjects wearing MSM will feel breathing discomfort, and the breathing discomfort becomes more and more intense with the environmental temperature increases. In a cold environment, wearing MSM has little effect on the three subjective feelings due to the heat dissipation of human body reduces. However, as the environmental temperature rises, the poor air permeability of the MSM leads to a very poor breathing comfort experience.

### 4.5 Comparison of steady TSV, TCV, and BCV

In Figure 10B, when wearing MSM, the neutral temperature is 24.6°C, and the temperature with the optimal thermal comfort in Figure 11B is 24.9°C. When the MSM is not worn, the neutral temperature in Figure 10B is 26.1°C, and the temperature with optimal thermal comfort in Figure 11B is 26.3°C. Although the neutral temperature is very close to the temperature with optimal thermal comfort, it should be noted that the temperature with optimal thermal comfort is slightly higher than the neutral temperature, which indicates that all subjects prefer environments with slightly higher temperatures than neutral. The experimental result is consistent with the research conclusions of Shahzad et al.\(^{49}\) and Humphreys.\(^{50}\) Exploring the reasons from the physiological adjustment methods, in a warm environment, heat dissipation can be enhanced by increasing breathing and perspiration. In a slightly cooler environment, the human body can only rely on reducing human body heat dissipation and increasing metabolic levels to maintain body temperature. In addition, according to the structure of the human body, the number of cold receptors is much greater than that of thermal receptors,\(^{51}\) the cold receptors are located 0.15–0.17 mm below the skin surface, and thermal receptors are located 0.3–0.6 mm below the skin surface,\(^{52,53}\) which makes the human body more sensitive to cold stimulation.\(^{54}\) As mentioned above, the subjects prefer to a slightly warm environment, even in summer.

### 4.6 Limitations

The experiment only studied the three-layer MSM produced by one manufacturer, and the difference between other masks (four-layer, cotton, etc.) is not considered. The experimental MSM is the ear-mounted, and the effect of ear discomfort on subjective voting is not considered in the experiment. Compared with the slightly older staff, the subjects are all healthy college students who have better physical fitness, more vitality, and no fertility or occupational diseases (joint diseases such as the cervical spine). In addition, the psychological considerations have not been made to link the mask and all the possible impediments to breathing and thermal comfort votes.

### 5 Conclusion

By collecting subjects’ physiological data and subjective perception voting, the paper evaluates the effects of local thermal stimulation caused by MSM on the human thermal psychological under different indoor thermal conditions and explores the distortion power of MSM.

1. Wearing MSM has a significant impact on the subjective comfort of the human body. Wearing MSM can cause a sharp increase
of thermal sensation with the maximum increase of TSV by 2.4, but also result in a sharp decrease of thermal comfort with the maximum decrease of TCV by 2.7. Wearing MSM can also cause breathing discomfort, and this discomfort will become more and more intense as the temperature increases.

2. Wearing MSM can reduce the neutral temperature by 1.5°C and the environmental temperature with optimal thermal comfort by 1.4°C. When the office staff wears an MSM for a long time, the decrease of environmental temperature can improve human comfort.

3. According to the fitting results of subjective voting, whether wearing a mask or not, the most comfortable environment temperature is slightly higher than the environmental temperature with neutral thermal sensation, which indicates that the subjects prefer a slight temperature environment.

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NOMENCLATURE

| Abbreviation | Description |
|--------------|-------------|
| BCV          | breathing comfort vote |
| TCV          | thermal comfort vote |
| TSV          | thermal sensation vote |
| No MSM       | no medical surgical mask |
| MSM          | medical surgical mask |
| $t_o$        | environmental temperature, °C |
| RH           | relative humidity of indoor air, % |
| $v$          | indoor air velocity, m/s |

CONFLICT OF INTERESTS
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.

AUTHOR CONTRIBUTIONS
Ruhang Zhang took a lead in conceptualization, investigation, writing-original draft, formal analysis, project administration, methodology, and writing-review and editing. Jianhua Liu, Liang Zhang, and Jindi Lin played a supporting role in writing-review and editing. Qingqing Wu supported in software development.

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