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Employing the spray system to improve the regional thermal environment in outdoor open space

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ABSTRACT

Rapid urbanization has led to a significant urban heat island effect. When the spray cooling system is applied to outdoor public space, it is helpful to improve the microclimate. While a reasonable spray system is an important guarantee to improve the thermal comfort of the human body in the spray space. In this study, the combination of experimental measurement and questionnaire survey was used to explore the thermal comfort index suitable for evaluating natural and spray space to modify the heat stress scale. The accuracy of thermal sensation prediction based on the original thermal comfort index and the corresponding heat stress scale was compared between the two methods of thermal sensation regression and thermal unacceptable percentage prediction. A heat stress scale based on natural and spray space in Qingdao was proposed. The results showed that compared with direct exposure to sunlight, the spray space could effectively improve thermal sensation (−1.07) and thermal comfort (+0.80), and inhibit the rate of skin temperature rise (+0.553 ~ −0.155 °C/min). The thermal unacceptable percentage method can be used to predict the thermal sensation in the natural space, and the prediction rate (88 %) of the universal thermal climate index (UTCI) was the highest. The thermal sensation regression method can be used to predict the thermal sensation in the spray space, and the standard effective temperature (SET*) prediction rate (60 %) was the highest. In the assessment of outdoor thermal risk, when the UTCI exceeded 38 °C in Qingdao, the heat risk reached the range of strong heat stress, and it was necessary to start the spray device to improve the thermal environment. When the SET* in the spray space exceeded 41 °C, the spray still cannot improve the thermal health status, and it was recommended to reduce outdoor activities.

1. Introduction

Rapid urbanization has led to a significant urban heat island effect, thus exacerbating the high temperature intensity in urban areas (Liu et al., 2024). Studies have shown that changes in underlying surface properties, anthropogenic heat and greenhouse gas emissions have an important impact on heat island intensity (Zhao et al., 2024a). In the high temperature zone, the air density and the air pressure are low. The generated cyclonic updraft will supplement various waste and chemical harmful gases to the urban area, thus endangering human health (Chen et al., 2023). The need for space cooling is increasing, and how to introduce sustainable urban cooling has become an urgent consideration for planners and architects. It is a common and convenient method to improve the urban microclimate by absorbing heat from plants or water (Han et al., 2024). In terms of water, the spray system is favored for its efficient

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Nomenclature

D	Black globe diameter (m)
G	Global radiation (W/m^2)
R^2	Coefficient of determination
T_a	Air temperature (°C)
T_{cr}	Core temperature (°C)
T_g	Globe temperature (°C)
T_i	Skin temperature, i is part of the body (°C)
T_{mrt}	Mean radiation temperature (°C)
T_{Msk}	Mean skin temperature (°C)
T_{sk}	Skin temperature (°C)
v_a	Air velocity (m/s)
ε_g	Black globe emissivity
HAV	Humidity acceptability vote
HPV	Humidity preference vote
HSV	Humidity sensation vote
MHSV	Mean humidity sensation vote
MTSV	Mean thermal sensation vote
MTCV	Mean thermal comfort vote
PET	Physiological equivalent temperature (°C)
RH	Relative humidity (%)
SET*	Standard effective temperature (°C)
TAV	Thermal acceptability vote
TCV	Thermal comfort vote
TPV	Thermal preference vote
TSV	Thermal sensation vote
UTCI	Universal thermal climate index (°C)

evaporation to achieve rapid cooling (Lu et al., 2023). However, in view of the uneven distribution of high temperature in the city, the linkage reaction and cooperative work between the operation setting of the spray system and the microclimate and human thermal comfort need to be explored to build a cooler and more livable city.

The improvement of thermal environment and thermal comfort by spray system has been confirmed (Gao et al., 2023a). Atieh and Shariff (2013) found that the solar spray system could reduce the air temperature (T_a) by more than 10 °C and increase the maximum relative humidity (RH) by about 25 % in the subtropical desert climate. Ishii et al. (2009) set up a spray system on the platform of a taxi station and found that the spray system can reduce the T_a by 2 °C. Kim and Kang (2023) used computational fluid dynamics to explore the relationship between meteorological parameters and spray cooling effect. The research showed that when the initial T_a was set to 45 °C, the RH was 90 %, and the wind speed (v_a) was 1 m/s, the T_a was reduced by 8.92 %. Xie et al. (2024) carried out spray experiments in semi-outdoor spaces and found that spray could reduce T_a by 2.4–4.9 °C and increase RH by 17.1–17.8 %. Ulpiani and Zinzi (2023) found that the maximum cooling temperature of the spray could exceed 6.5 °C in the Mediterranean climate zone. After adding a windshield device, although the temperature could drop by 10 °C, the humidity would increase significantly. Lu et al. (2023) used the spray system to improve the thermal environment of the hardened pavement, and the research showed that the spray reduced the T_a by 1.43 °C. Coccia et al. (2023) found that the dry bulb temperature could be reduced by −20 % when using the optimal configuration of the spray system in Ancona, Italy. Sun et al. (2024) analyzed the cooling benefits of the spray system applied in the courtyard in Seville, Spain. The results showed that evaporative cooling could reduce the temperature by 2.06 °C and increase the humidity by 4.29 %. Wang et al. (2024) used spray cooling to solve the overheating problem of double-layer facades. The research showed that when the outdoor RH was 20 %, the spray cooling efficiency reached 28.2 %. However, when the RH rose to 80 %, the spray cooling efficiency dropped to only 9.3 %. Although the spray system can reduce the T_a, too high RH will cause discomfort to the human body. Therefore, some scholars have explored the cooling and humidification balance of the spray system.

The heat exchange between human body and environment mainly includes convection, radiation and evaporation. When the spray system is used to achieve the evaporative cooling effect, the RH will increase significantly, and the saturated water vapor pressure on the surface of the human skin and the water vapor pressure difference in the air will decrease, which will slow down the water evaporation rate on the skin surface and reduce the sweat heat dissipation efficiency, resulting in an increase in thermal sensation (McIntyre, 1980). Farnham et al. (2011) found that a single nozzle with Sauter mean droplet diameter of 41 μm can provide cooling of 0.7 K without wetting. Ulpiani et al. (2019a) used fuzzy intelligent control theory to control the RH at 51.2–67.5 %, and the T_a was reduced by 6.14–7.5 °C, which improved the spray efficiency. Therefore, the human comfort in the spray environment is affected by the thermal parameters, which plays an important reference role in the control design of the spray system (Gao et al., 2023b). The experimental study of Zhang et al. (2021) showed that the spray system can reduce the T_a of the head, nasal cavity and chest by 2.6 °C, 2.1 °C and 3.3 °C respectively in the waiting area of the bus station. Oh et al. (2020a) found that spray evaporative cooling could reduce

T_{sk} by 0.53 °C. The prediction model of Li et al. (2022) showed that T_{sk} in mist spraying decreased 0.21 °C when T_a declined 1 °C with constant RH and T_{mrt}. Zheng et al. (2019) found that the main factors affecting the change of thermal sensation in spray were skin temperature (T_{sk}) and humidity sensation vote (HSV), and the mean radiation temperature (T_{mrt}) and RH affected the change of thermal comfort. Gao et al. (2023a) explored the effect of water mist stimulation on the dynamic thermal response of pedestrians in summer, and found that under the 2–5 min water mist exposure time, the change of thermal sensation to cold stimulation was about 1.5 times that of thermal stimulation. Meng et al. (2022) found that the spray system with a flow rate of 30 ml/min can improve the thermal comfort by 2.85. Su et al. (2022) found that the skin temperature in the spray environment could decrease by 0.45 °C, and the thermal sensation vote of the subjects was opposite to the humidity trend.

In addition to analyzing the physiological and psychological changes in the thermal response of the human body caused by the climate field of the spray system, existing thermal indexes have been introduced to evaluate the thermal environment and thermal comfort in the spray space, such as the physiological equivalent temperature (PET), the standard effective temperature (SET*) and the universal thermal climate index (UTCI) (Oh et al., 2020b).

Ulpiani et al. (2019b) found that spray can reduce SET*, PET and UTCI by an average of 1.7 °C, 2.0 °C and 0.9 °C, respectively. Su et al. (2022) established a numerical model of nozzle density and height to predict the neutral UTCI in the spray space. The experimental study of Desert et al. (2020) showed that the UTCI value in the spray space can be reduced by 15 °C compared with the natural space. Li et al. (2022) evaluated the category of heat stress in spray, and the results showed that the UTCI value of spray shadow space was 12.31 °C lower than that of sunlight.

Huang et al. (2011) applied the spray system to an exhibition hall of Shanghai World Expo and found that the WBGT value can be reduced by 3.5–5.2 °C in spray. Zhao et al. (2024b) explored the cooling distribution when the spray system was applied to the school courtyard and found that PET was reduced by an average of 2.9 °C compared to the original exposed area. Zheng et al. (2019) considered that SET* developed under rest or motion cases cannot fully capture the cooling factors of dry fog, because the additional heat loss caused by droplets was not considered.

Oh et al. (2019, 2020a, 2020b) pointed out that only using ordinary objective parameters to evaluate the spray environment would underestimate the cooling effect of the system. Therefore, the additional heat loss of skin surface evaporation caused by spray was considered in the SET* model to improve the accuracy of evaluating thermal sensation under spray. In addition, it was found that SET*, PET, WBGT and UTCI cannot fully represent the thermal sensation and comfort in the spray space, while the two-node model predicted the T_{sk} accurately. Therefore, a new index for evaluating the thermal sensation of outdoor and spray space was proposed. Table 1 reviewed the improvement of thermal comfort index value in spray space.

In these studies, the existing outdoor thermal index is more used to evaluate the spray environment, and there is a lack of comprehensive correlation analysis between the thermal index and the thermal response in the spray space and the basis for selecting the thermal index evaluation. At the same time, the outdoor meteorological variables are more diverse, while the superposition of spray makes this variable more complex. In view of the particularity of solar radiation (G), T_a, RH and v_a in the spray space, a new scale evaluation of the thermal comfort index should be carried out.

The contribution of this study is that it clarifies the influence of microclimate changes caused by spray on thermal response and fills the gap in the study of applicable thermal comfort index discrimination and heat stress scale correction in spray space. The selection of thermal comfort index in the spray space has important reference significance. This study first explored the changes of meteorological parameters, thermal comfort evaluation and physiological parameters with time in the natural and spray space. Secondly, the thermal

Table 1
The improvement of thermal comfort index value in spray space.

City	Climate zone	Index	Conclusion	Reference
Rome	Continental climate	SET*, PET, UTCI	The spray can reduce SET*, PET and UTCI by an average of 1.7 °C, 2.0 °C and 0.9 °C, respectively.	Ulpiani et al., 2019a
Xi'an	Humid subtropical climate	UTCI	The UTCI value decreases by 1.188 °C for every 0.82 m decrease in nozzle height or one increase in nozzle number.	Su et al., 2022
Antofagasta	Hot, humid climate	UTCI	Spray can reduce the UTCI value by 15 °C.	Desert et al., 2020
Xi'an	Humid subtropical climate	UTCI	Spray can reduce the UTCI value by 8.03 °C.	Li et al., 2022
Shanghai	Hot, humid climate	WBGT	Spray can reduce the WBGT value to 3.5–5.2 °C.	Huang et al., 2011
Hunan	Hot, humid climate	PET	Spray can reduce the PET value by 0.7–4.4 °C.	Zhao et al., 2024a
Singapore	Hot, humid climate	SET*	Spray can reduce the SET* value by 2.2 °C.	Zheng et al., 2019
Tokyo	Humid Subtropical Climate	SET*	Spray can reduce SET* (2NM) 1.57 °C, SET* (3NM) 1.66 °C.	Oh et al., 2019
Tokyo	Humid Subtropical Climate	SET*, PET, UTCI, WBGT	Only SET* is possible to accurately predict MTSV in spray space.	Oh et al., 2020a
Tokyo	Humid Subtropical Climate	SET*, PET, UTCI	The spray can reduce SET*, PET and UTCI by an average of 1.1 °C, 2.2 °C and 1.7 °C, respectively.	Oh et al., 2020b
Tokyo	Humid Subtropical Climate	SET*	Spray can reduce SET* (2NM) 1.57 °C, SET* (3NM) 1.66 °C.	Oh et al., 2019

response was related to the thermal comfort index. The thermal comfort index adapted to different cases was discussed, and the corresponding heat stress scale was modified. Finally, the accuracy of thermal sensation prediction was compared by the modified heat stress scale. The research is helpful to enhance the evaluation of pedestrian thermal comfort and puts forward thermal health suggestions and overheating risk warnings.

2. Methods

2.1. Experimental platform

The spray cooling system is widely used in urban streets in summer, and the cooling and humidifying scene created by it has a significant impact on pedestrian thermal response. The experiment was carried out in Qingdao University of Technology, China. By creating a spray environment, the subjects were simulated to be exposed to sunlight and spray space in outdoor activities in summer, and the heat stress scale changes associated with the thermal response were quantified and compared when the spray cooling system was added. The experimental platform is shown in Fig. 1. The nozzle was installed on a 3 m (length) × 2.7 m (height) bracket. The nozzle aperture was 0.3 mm and the flow rate was 0.1 l/min. There were four nozzles arranged on each support, and the distance between nozzles was 0.75 m. The bracket spacing was 2.1 m, which was designed according to the normal sidewalk spacing. The output pressure of the high-pressure pump was 0.55 MPa. The water temperature was natural.

2.2. Experimental process

The experimental process is shown in Fig. 2. Before the formal experiment, the subjects rested in the preparation room for 30 min to reach a neutral thermal state. In the preparation room, T_a was 26 °C, RH was 55 % ~ 65 %, v_a was less than 0.1 m/s, and T_{mrt} was close to T_a. The subjects were exposed to natural and spray space, respectively. The process of natural case was that the subjects sat in the preparation room for 30 min and then directly entered the sunlight and walked slightly for 15 min. The subjects were asked to fill in the questionnaire at 0, 2, 5, 10, 15 min, and the core temperature (T_{cr}) was measured at 0 and 15 min. The T_{sk} was continuously tested during the experiment. Spray case was the same as natural case, and the only difference was that the subjects directly enter the spray space after sitting for 30 min from the preparation room. In the outdoor test, the subjects maintained a walking speed of 0.9 m/s and a metabolic rate of 2 met. The walking speed was controlled by the metronome. The experiment was not carried out simultaneously in natural space and spray space. The sequence was randomly generated to control the sequence deviation, and the subjects may first conduct experiments in natural space or spray space to prevent the influence of thermal history on subjective voting and reduce experimental errors.

2.3. Micrometeorological measurements

The instruments for measuring T_a, RH, globe temperature (T_g), v_a, and G in the sunlight and spray were arranged at 1.1 m from the ground, and the data were recorded every 1 min, lasting from 10:00 to 16:00 (ASHRAE Handbook-Fundamentals, 2021). The instrument is shown in Fig. 3. Too high or too low test points for the measurement of non-uniform thermal environment would lead to data deviation. The instrument was 5 m away from the spray platform in the natural space to minimize the impact of spray on the accuracy of the equipment. The measurement range and accuracy are shown in Table 2, and the resolution and accuracy are in accordance with the ISO 7726 standard (ISO, International Standard 7726, 1998). The T_{mrt} was calculated as follows:

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{\left(1.10 \times 10^8 \times {v_a}^{0.6}\right)}{\left(\varepsilon_g \times D^{0.4}\right)} \times \left(T_g - T_a\right) \right]^{0.25} - 273.15 \quad (1)$$

where D is the globe diameter ($D = 0.05$ m in this study), and ε_g is the emissivity ($\varepsilon_g = 0.95$ in this study).

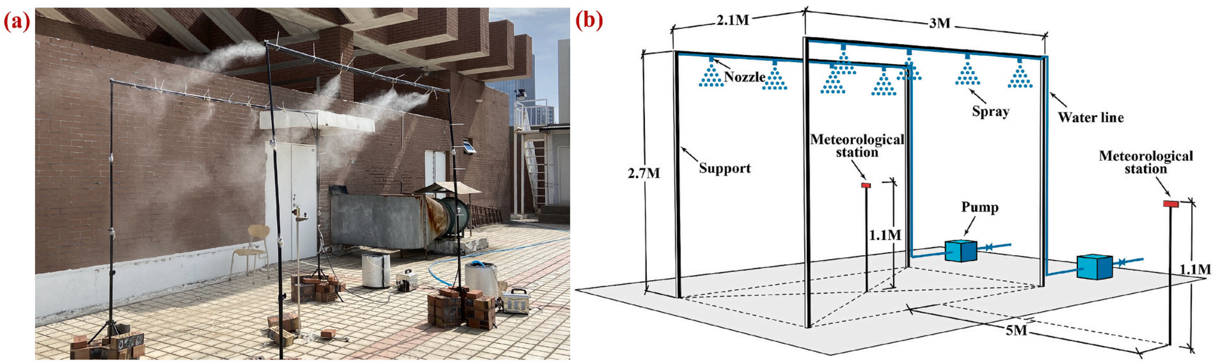

Fig. 1. Model of experimental platform.

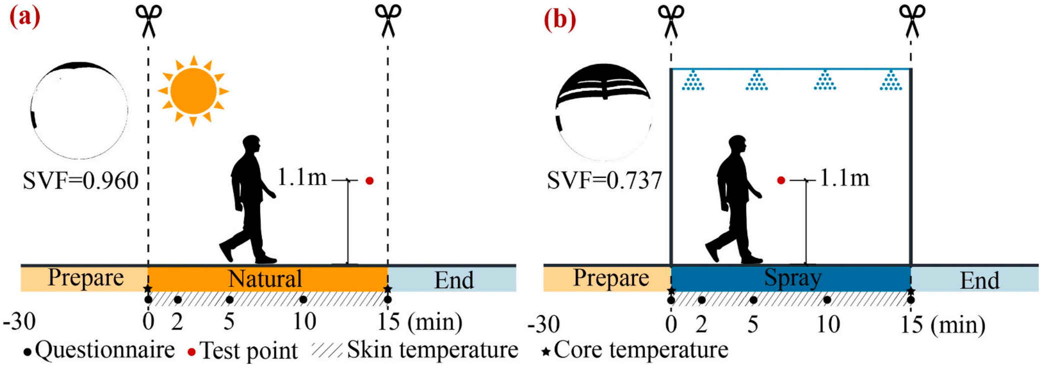

Fig. 2. Experimental process of (a) outdoor natural environment and (b) outdoor spray environment.

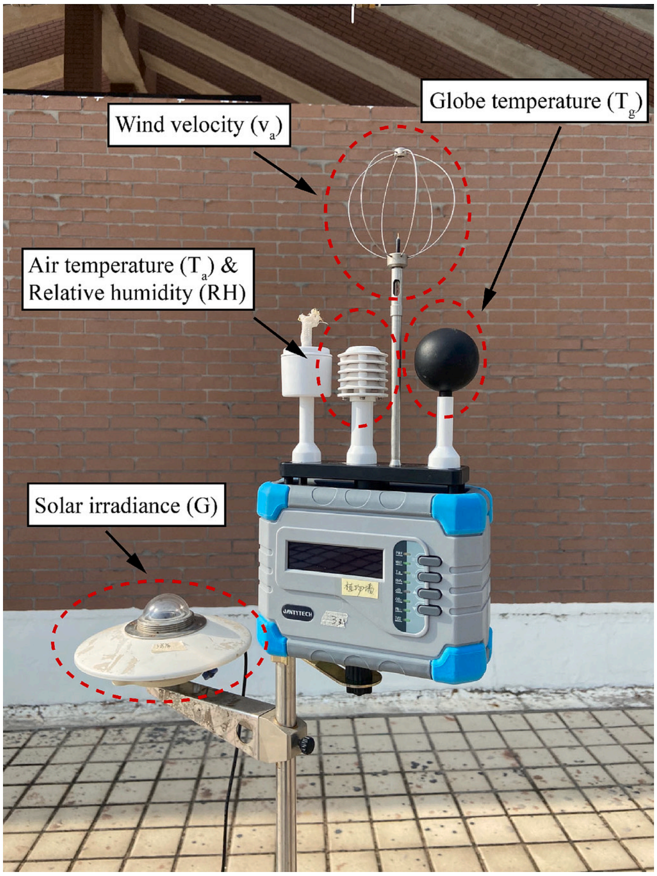

Fig. 3. Meteorological parameter measuring instruments.

2.4. Physiological measurements

Physiological measurements are T_{sk} and T_{cr}, and the instrument accuracy is shown in Table 2. The T_{sk} measuring instrument used iButton to record the data every 5 min. The T_{cr} measuring instrument used a mercury thermometer, and the test duration was 5 min. In the experiment, the T_{sk} was measured by three-point method, which were left chest, left lower arm and left lower leg. In the non-uniform thermal environment, the local measurement points at different heights of the human body are conducive to the estimation of the mean skin temperature (T_{Msk}). The selection of the two parts of the arm and leg that are directly exposed to the sunlight is more representative in the outdoor thermal comfort evaluation (Kurazumi et al., 2018). The iButton was connected to the body 30 min in advance to allow the sensor to adapt to changes in T_{sk} before the start of the formal experiment. The T_{Msk} was calculated as follows (Burton, 1935):

Table 2
Measurement rang and accuracy of meteorological and physiological parameters of the instrument.

Sensor	Parameters	Variable	Measuring range	Accuracy
JT-IAQ-50	T_a (°C)	Air temperature	−20 ~ +125 °C	±0.2 °C (+10 ~ +50 °C)
	RH (%)	Relative humidity	0 % ~ 100 %	±3 %
	v_a (m/s)	Wind speed	0.05–5 m/s	±(0.03 m/s + 2 %)
	T_g (°C)	Globe temperature	−20 ~ +85 °C	±0.2 °C (+10 ~ +50 °C)
JTR05	G (W/m^2)	Solar irradiance	0–2000 W/m^2	±2 %
iButton DS1925	T_{sk} (°C)	Skin temperature	−40 ~ +85 °C	±0.5 °C
CR. W11	T_{cr} (°C)	Core temperature	35–42 °C	+0.1 °C ~ -0.15 °C

$$T_{Msk} = 0.5T_{Chest} + 0.14T_{Arm} + 0.36T_{Leg} \tag{2}$$

where, T_{Msk} means mean skin temperature, °C, and T_{Chest}, T_{Arm}, and T_{Leg} are local skin temperatures on the chest, the lower arm, and the lower leg, °C.

2.5. Questionnaire survey

Before the formal experiment, G* Power was applied to estimate the sample size. The significance level α was set to 0.05, and the power level was set to 0.8. According to the research of Lan et al. (Lan and Lian, 2010), the effect size of subjective ratings and physiological measurements were set to 0.4 and 0.5, and the minimum sample size was calculated to be 16. Therefore, a total of 16 subjects were recruited in this study, including 8 males and 8 females. All 16 subjects participated in the experiment of spray and natural space. The characteristic data are shown in Table 3. The participants were all students who had lived in Qingdao for more than one year. They were asked to wear summer clothes (short T-shirts and shorts) to carry out the experiment. Before the experiment, participants were not allowed to drink coffee, alcohol or do strenuous physical exercise and were encouraged to do some light work.

In order to comprehensively evaluate the thermal comfort, as shown in Table 4, the thermal sensation vote (TSV), humidity sensation vote (HSV) and thermal comfort vote (TCV) were divided into 7-point scale, the thermal acceptability vote (TAV) and humidity acceptability vote (HAV) were divided into 4-point scale, and the thermal preference vote (TPV) and humidity preference vote (HPV) were divided into 3-point scale, so as to accurately evaluate the subjects' sense and acceptability of heat and humidity. The subjective feeling of the participants can effectively reflect the influence of the spray system on the thermal comfort and the acceptability to the spray system. At the same time, thermal preferences in sunlight and spray were also included in the questionnaire survey to assess the subjects' thermal benchmarks and deficiencies in the spray system.

2.6. Statistical analysis

The data were analyzed by IBM SPSS statistics 27.0.1 software. Statistical analysis includes: (1) Spearman correlation analysis. The main factors affecting thermal sensation were analyzed by examining the correlation between thermal sensation, meteorological parameters and skin temperature. (2) Linear regression analysis. The regression analysis of thermal sensation, thermal unacceptable percentage and thermal comfort index was carried out to calculate the modified thermal stress range of different cases. Check whether the linear regression model meets the statistical hypothesis, and perform the F test to verify the significant linear relationship between the independent variable and the dependent variable. Origin 2022 software was used to fit the regression equation and calculate the accuracy index R^2. The regression analysis was based on 95 % confidence interval. (3) The significance tests were two-tailed. The *p*-value was used to determine the statistical significance of the results. In this study, when the p- value is less than 0.05, the difference was considered to be significant.

3. Results and discussion

3.1. Dynamic variations of air temperature and relative humidity

Qingdao has a monsoon-influenced-hot-summer humid continental climate (Dwa) within the Köppen climate division. The experimental site is rigidly paved within 10–20 m, 3.5 km from the seaside, and there is no additional evaporative cooling greening or water body. The meteorological parameters at 1.1 m in the natural and spray space are shown in Table 5. The T_a and RH at 1.1 m in the natural and spray space were compared, as shown in Fig. 4. The results showed that the mean T_a in spray space was 2.01 °C lower than

Table 3
Participant characteristic date (Mean ± SD).

Gender	Sample size	Age (y)	Height (m)	Weight (kg)	Clothing insulation (clo)	Metbolic (met)
Male	8	25.29 ± 1.25	179.57 ± 3.26	85.71 ± 4.35	0.38 ± 0.00	1.03 ± 0.08
Female	8	25.13 ± 1.73	166.13 ± 4.12	54.00 ± 5.16	0.45 ± 0.04	1.11 ± 0.04
Total	16	25.20 ± 1.47	172.40 ± 7.83	68.80 ± 17.02	0.43 ± 0.04	1.07 ± 0.07

Table 4
Scales of questionnaire parameters.

Scale	TSV	HSV	TCV	TAV	HAV	TPV	HPV
+3	Hot	Very humid	Very comfortable	–	–		
+2	Warm	Humid	Comfortable	Completely acceptable	Completely acceptable		
+1	Slightly warm	Slightly humid	Just comfortable	Just acceptable	Just acceptable	Cooler	Drier
0	Neutral	Neutral	Neutral	–	–	Unvaried	Unvaried
−1	Slightly cool	Slightly dry	Just uncomfortable	Just unacceptable	Just unacceptable	Warmer	Damper
−2	Cool	Dry	Uncomfortable	Completely unacceptable	Completely unacceptable		
−3	Cold	Very dry	Very uncomfortable	–	–		

that in natural space, and the mean RH was 9.08 % higher. The maximum value of T_a can be reduced by 4.2 °C, and the minimum value was 0.4 °C. The maximum value of RH increase was 18.46 %, and the minimum value was 3.58 %. The drastic change of T_a and RH in spray may be due to the deposition of incompletely atomized droplets on the measuring probe. Because the water mist has the potential to reflect near-infrared light, it has scattering and absorption effects on thermal radiation, thereby reducing the short-wave radiation (Dombrovsky et al., 2011). In addition, since some droplets may deposit on the ground, the ground long-wave radiation will be reduced, so the G and T_g in the water mist space are lower than those in the natural space.

The spray system mainly relies on the evaporation of water droplets to absorb heat for cooling, so the outdoor thermal environment parameters, especially the RH, have a great influence on the degree of cooling. The relatively saturated water vapor in the air is not conducive to the evaporation of water mist. If the spray system is used improperly, the higher RH will reduce the outdoor comfort (Ulpiani et al., 2019b, 2020).

3.2. Dynamic variations of thermal response

3.2.1. Thermal sensation, thermal comfort and humidity sensation

Fig. 5 shows the changes of TSV, TCV and HSV over time in the natural and spray space. Within 15 min in the natural space, mean thermal sensation vote (MTSV) increased from +2.20 (warm) to +2.93 (warm), mean thermal comfort vote (MTCV) decreased from −1.60 (slightly uncomfortable) to −2.73 (uncomfortable), mean humidity sensation vote (MHSV) decreased from +0.47 (neutral) to −0.33 (neutral), and the number of participants who felt hot, uncomfortable and dry for the environment increased significantly. Within 15 min in the spray space, because the spray system reduced the T_a and increased the RH, MTSV decreased from +1.67 (slightly warm) to +0.60 (neutral), MTCV increased from −1.00 (just uncomfortable) to −0.20 (neutral), and MHSV increased from +0.27 (neutral) to +1.53 (slight humid).

Spearman correlation analysis was performed on TSV, TCV and HSV, respectively. The results showed that the coefficients of TSV and TCV were − 0.798**, indicating that the increase of thermal sensation would lead to the increase of discomfort. The coefficient of HSV and TCV was 0.419**, suggesting that in the dry summer, moderate humidity could make people feel comfortable. The coefficient of HSV and TSV was −0.407**, indicating that the increase of humidity would lead to the increase of thermal sensation.

3.2.2. Thermal preference and thermal acceptability

The thermal preference votes of T_a and RH in the natural and spray space were counted. As shown in Fig. 6(a) shows that the subjects expected the T_a to decrease whether in the natural or spray, and the number of subjects who expected the T_a to decrease in the natural space was more than that in the spray, indicating that the spray system had an effect on the improvement of the thermal environment and the thermal comfort. After entering the spray space for 10 min, 33 % of people wanted the T_a to remain unchanged, an increase of 6 % compared to 0 and 5 min. The T_{sk} began to decrease after 10 min in the spray space, indicating that the evaporation of the spray triggers the cold receptor on the surface of the skin, and the human body can feel the cool feeling brought by the spray system. For RH preference, as shown in Fig. 6(b), subjects in the spray space expected a decrease in RH more than in the natural, and this expectation gradually became stronger over time. The number of subjects expecting a decrease in RH increased from 33 % to 80 %.

Statistics on the acceptability of thermal and humid environments in the natural and spray space are shown in Fig. 7. Fig. 7(a) shows that the participants gradually felt hot and dry in the natural with the passage of time, and the completely unacceptable proportion of T_a rose from 33 % to 53 %. In the spray space, due to the cooling effect of the spray, the completely acceptable proportion was 13 % in 0–10 min and rose to 20 % in 15 min. Fig. 7(b) shows that the proportion of humidity unacceptable vote in the natural

Table 5
Microclimate parameters under the sunlight and spray space (July 10, 2023).

Environment condition		T_a (°C)	RH (%)	v_a (m/s)	G (W/m^2)	T_g (°C)
Natural space	Max	34.1	81.9	4.85	1139	42.6
	Min	29.1	61.9	0.5	273	32.9
	Mean ± SD	31.16 ± 1.01	69.66 ± 3.55	2.13 ± 1.01	742.35 ± 224.53	37.73 ± 2.21
Spray space	Max	32	89.5	4.23	984	38.6
	Min	26.2	68.9	0	271	27.3
	Mean ± SD	29.14 ± 1.01*	78.75 ± 3.86*	1.89 ± 1.06*	736.37 ± 171.00*	33.77 ± 2.52*

* The variable which encountered a significant change due to spray.

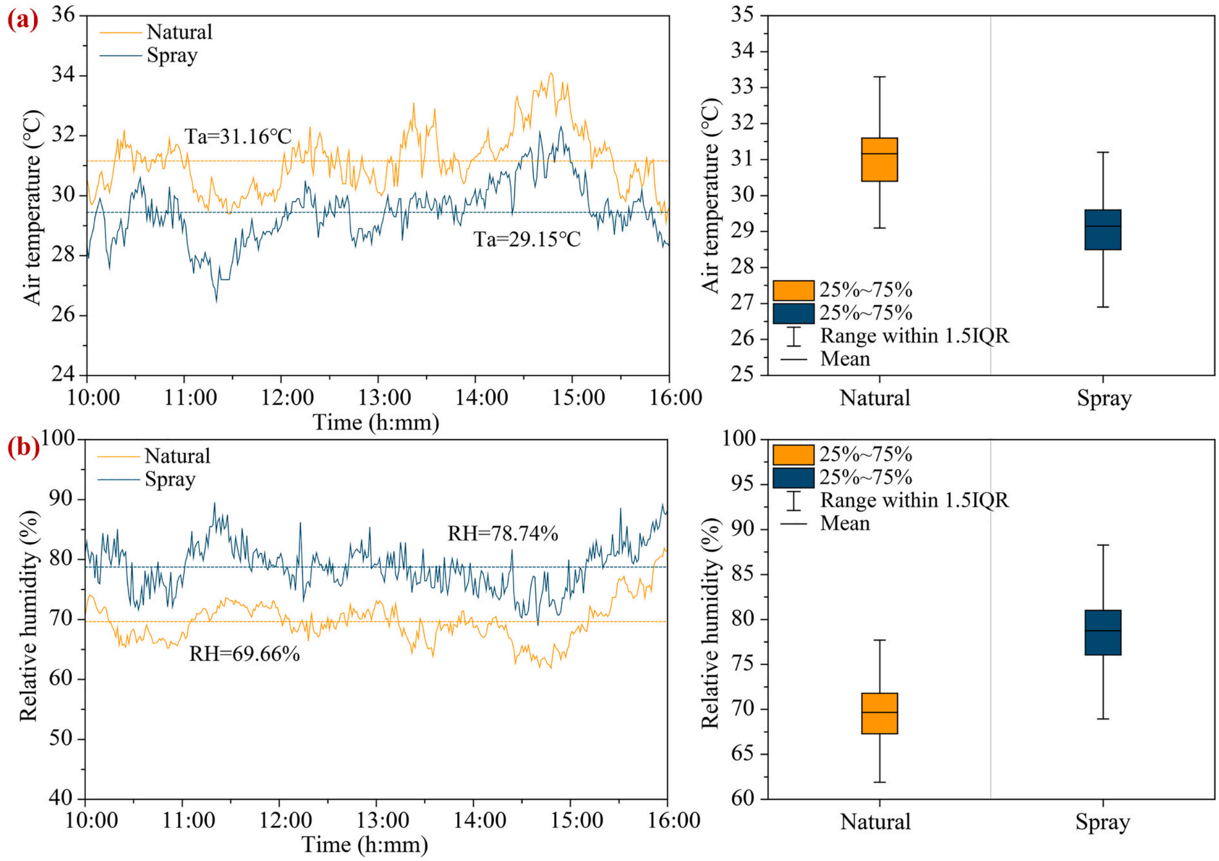

Fig. 4. Comparison of (a) T_a and (b) RH under different cases (July 10, 2023).

increased from 13 % to 33 % over time due to dry air. In the spray space, although acceptable accounted for the main part, the subjects felt wet due to the gradual increase of humidity on the skin surface, and the unacceptable proportion increased from 13 % to 46 % over time. In the outdoor open space, for the cooling benefits brought by the spray, compared with the natural space, the spray space with higher humidity was expected to be drier, but more acceptable to the subjects.

3.3. Dynamic variations of physiological parameters

3.3.1. Skin temperature

Fig. 8 shows the variations of T_{sk} at 0, 5, 10 and 15 min in the natural and spray space. The T_{sk} gradually increased with time in the natural space. The T_{Chest}, T_{Arm}, T_{Leg} and T_{Msk} increased by 2.28 °C, 2.87 °C, 2.96 °C and 2.61 °C respectively within 15 min, but the T_{sk} rise rate gradually decreased. The T_{sk} rise rate in 0–5 min (+1.042 °C/min) was about twice that in 5–10 min (+0.593 °C/min). In the spray space, the T_{sk} gradually increased from 0 to 10 min (+0.553 °C/min), while decreased from10 to 15 min (−0.155 °C/min). The increase of T_{sk} was lower than that in the natural, indicating that the spray could effectively inhibit the increase of T_{sk} in the early stage, and could reduce the T_{sk} in the later stage. The T_{Arm} decreased most significantly, which was 0.23 °C. It may be because the lower arm was more exposed than the chest, and compared with the leg, it was closer to the spray nozzle and can contact more mist and evaporate.

3.3.2. Core temperature

Fig. 9 shows the T_{cr} variations in the natural and spray space. After 15 min in the natural and spray space, the T_{cr} increased from 36.71 °C to 36.90 °C, 36.74 °C decreased to 36.72 °C, and the difference was 0.19 °C and 0.02 °C, respectively. Paired sample *t*-test was performed on T_{cr} before and after exposure. It was found that there was a significant difference in T_{cr} in the natural environment, but there was no difference in the spray space, indicating that 15 min of exposure in the natural space had an effect on the rise of T_{cr}, while the change of environmental parameters in the spray space had no significant effect on core temperature regulation. This may be that compared with the natural environment, the spray environment inhibits the rise of the T_{cr}.

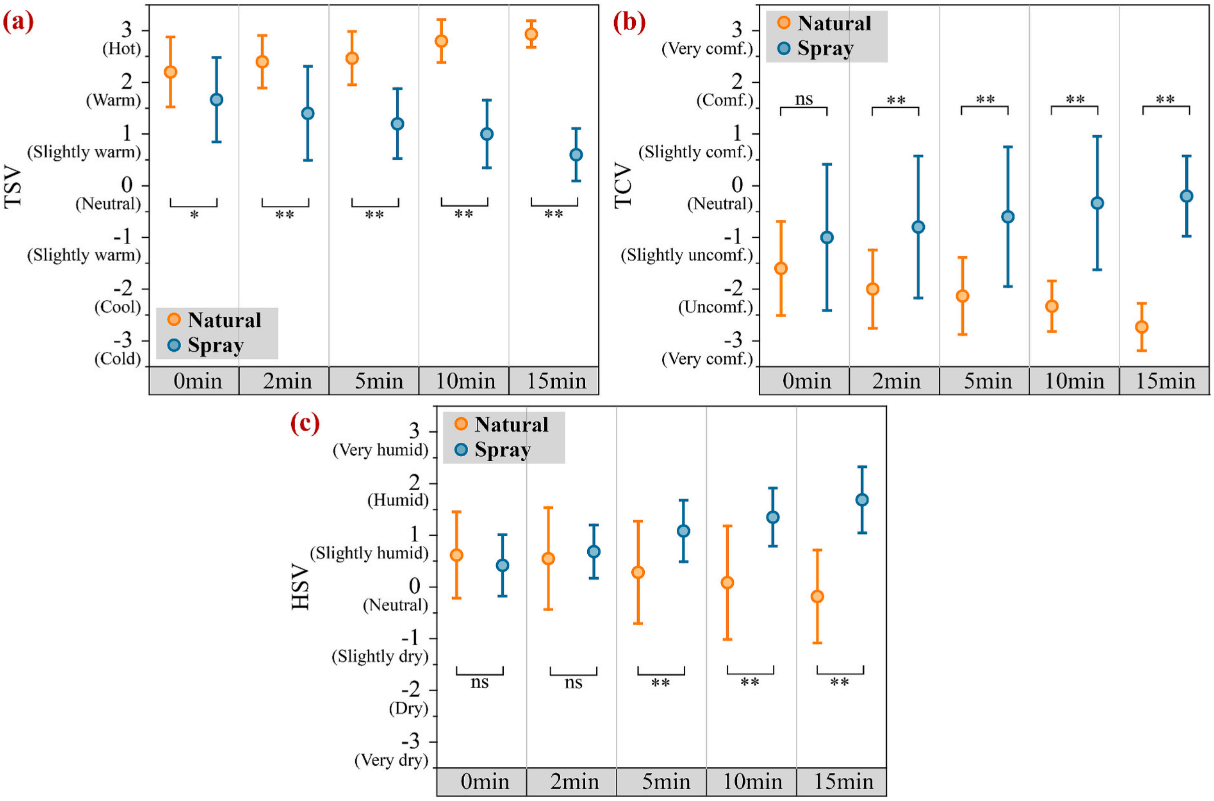

Fig. 5. Comparison of (a) TSV, (b) TCV and (c) HSV under different cases.

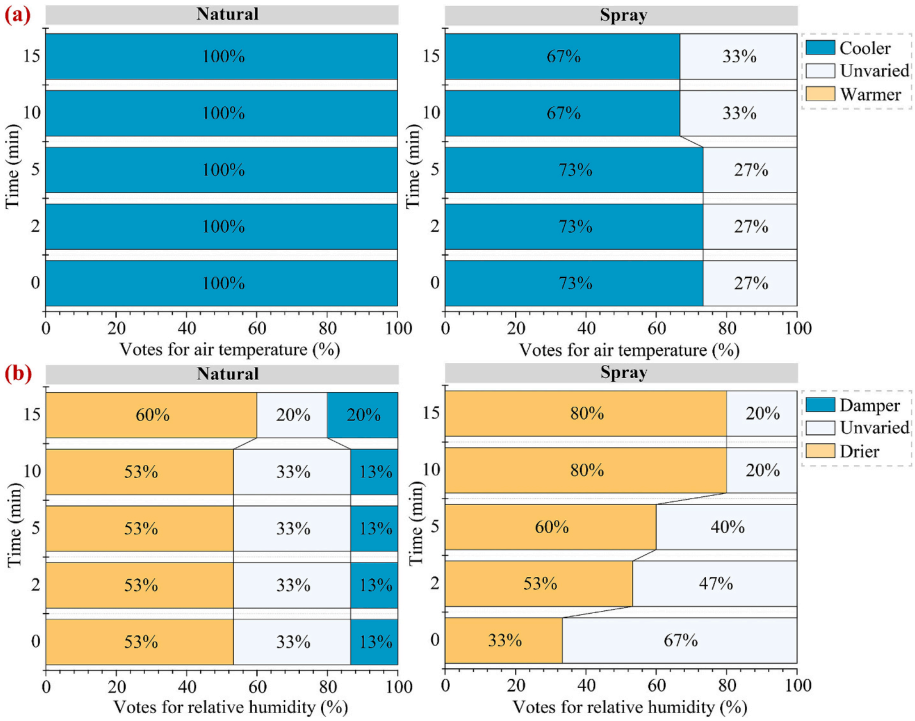

Fig. 6. Comparison of thermal preferences under different cases.

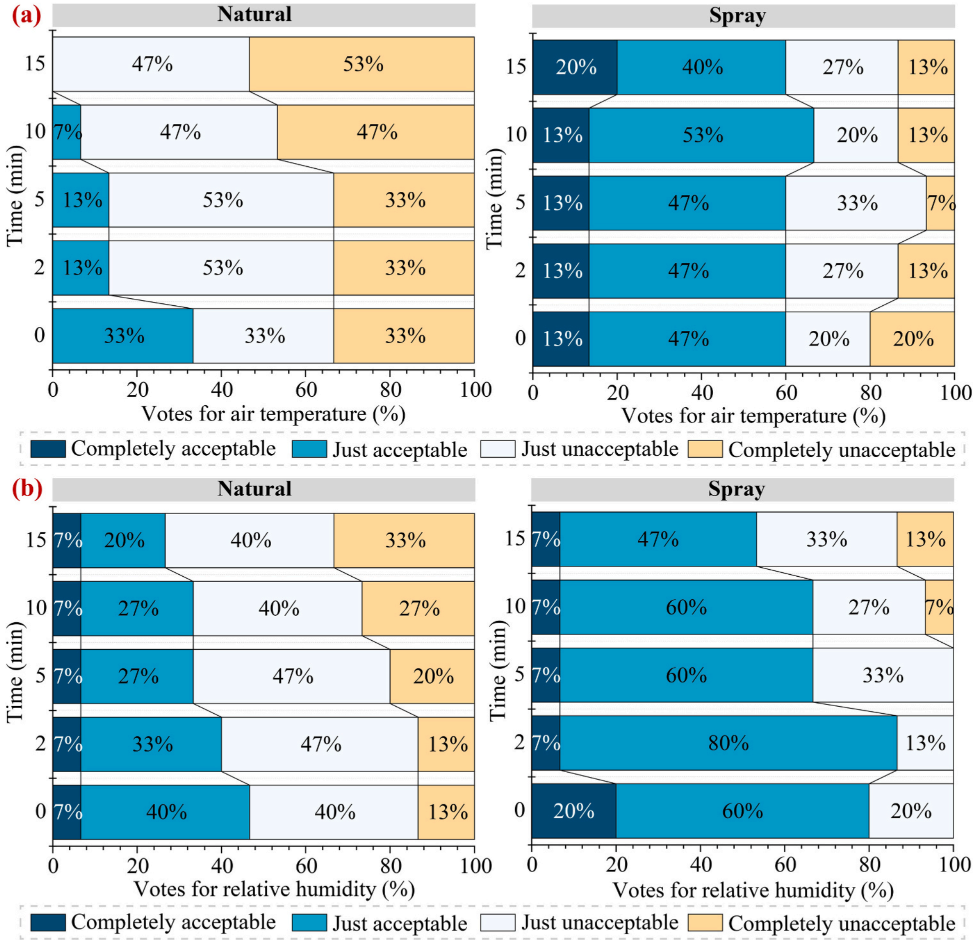

Fig. 7. Thermal acceptability comparison under different cases.

3.4. Correlation parameters of thermal response

Spearman correlation analysis was performed between TSV and meteorological parameters, as shown in Table 6. The results showed that in the natural environment, T_g, T_a, T_{mrt} were positively correlated with TSV, RH and v_a were negatively correlated, and T_g had the highest correlation. In the spray environment, T_g, T_a, T_{mrt}, v_a were positively correlated with TSV, RH was negatively correlated, and T_g had the highest correlation. There was no significant correlation between v_a and TSV in both natural and spray space. Compared with T_a and T_{mrt}, the T_g is used to measure the effective temperature of the human body when it is subjected to the radiation and convection in the radiant thermal environment, which can better correlate the thermal sensation of the combined effects of solar radiation.

In natural and spray space, TCV was negatively correlated with T_a, T_g and T_{mrt}, and positively correlated with RH and v_a. There was no significant correlation between v_a and TSV. It showed that the increase of sensible heat of temperature and radiation would reduce the thermal comfort, while the increase of latent heat of humidity would increase the thermal comfort. In addition, HSV was positively correlated with T_a and RH in natural and spray environment, and negatively correlated with T_g, v_a and T_{mrt}. T_a and T_g had no significant correlation with HSV. The HSV in each 2 % RH interval was averaged, and the MHSV value and its corresponding RH value were subjected to regression analysis. The equation was solved to establish the relationship between RH and MHSV. The results showed that when the humidity increased by 1 %, MHSV increased by 0.121.

Spearman correlation analysis was used to explore whether skin temperature can reflect thermal sensation, as shown in Table 7. The results showed that both local skin temperature and mean skin temperature were significantly positively correlated with TSV in the natural space, and T_{Leg} had the highest correlation with TSV. However, in the spray space, local skin temperature and mean skin temperature were negatively correlated with TSV, and only chest temperature was significantly correlated with TSV. This was because in the spray space, although the cooling effect of the spray improved the psychological thermal sensation of the human body, the skin temperature was still rising in the early stage due to the exposure of the sun. It was not until 10 min after the spray that the temperature of the skin surface began to decrease, so the psychological sensation was not consistent with the physiological changes. Due to the lag of T_{sk}, the T_{sk} and TSV of 10–15 min in the spray were analyzed. It was found that the local skin temperature and the T_{msk} were

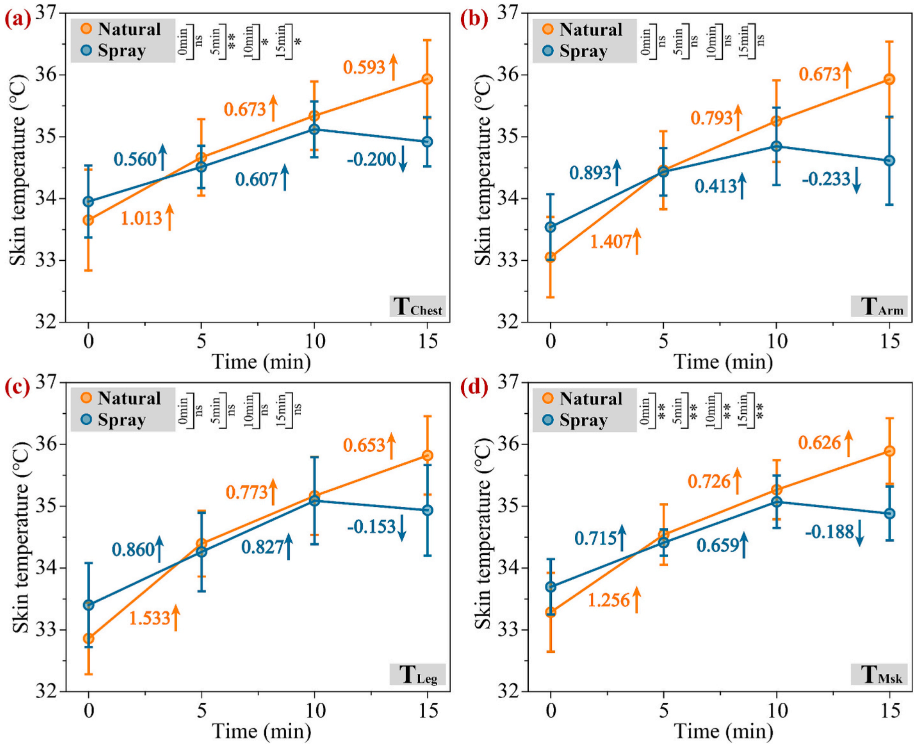

Fig. 8. T_{sk} comparison under different cases.

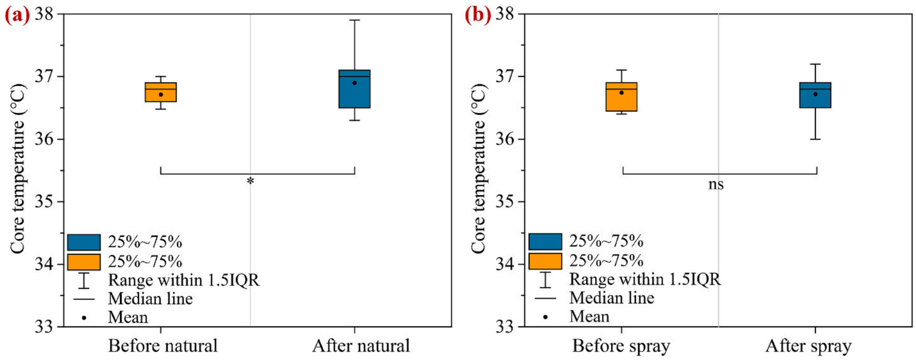

Fig. 9. Comparison of T_{cr} variations under different cases.

Table 6
Relationship between TSV and meteorological parameters.

Case	Parameter	T_a	RH	T_g	v_a	T_{mrt}
Natural space	TSV	**0.514****	**−0.489****	**0.790****	−0.012	**0.497****
	TCV	**−0.370****	**0.472****	**−0.578****	0.092	**−0.347****
	HSV	0.222	**0.247***	−0.197	**−0.524****	**−0.705****
Spray space	TSV	**0.482****	**−0.454****	**0.753****	0.002	**0.746****
	TCV	**−0.233***	**0.423****	**−0.658****	0.145	**−0.674****
	HSV	0.105	**0.438****	−0.219	−0.203	**−0.343****

significantly correlated with TSV, and T_{msk} had the highest correlation with TSV. In terms of local skin temperature, T_{leg} has the highest correlation.

Spearman correlation analysis of TCV, HSV and T_{sk} showed that TCV was negatively correlated with T_{sk} in natural space, indicating that the increase of T_{sk} would lead to the decrease of TCV. In the spray space, HSV was significantly positively correlated with T_{sk},

Table 7
Relationship between skin temperature and TSV.

Case	Parameter	T_{chest}	T_{Arm}	T_{Leg}	T_{Msk}
Natural space	TSV	**0.341****	**0.372****	**0.452****	**0.409****
	TCV	**−0.339****	**−0.368****	**−0.408****	**−0.388****
	HSV	−0.237	−0.146	−0.137	−0.197
Spray space	TSV (0–15 min)	**−0.378****	−0.117	−0.005	−0.206
	TSV (10–15 min)	**0.460***	**0.457***	**0.717****	**0.743****
	TCV	0.184	−0.034	−0.192	−0.023
	HSV	**0.363****	**0.297***	**0.380****	**0.474****

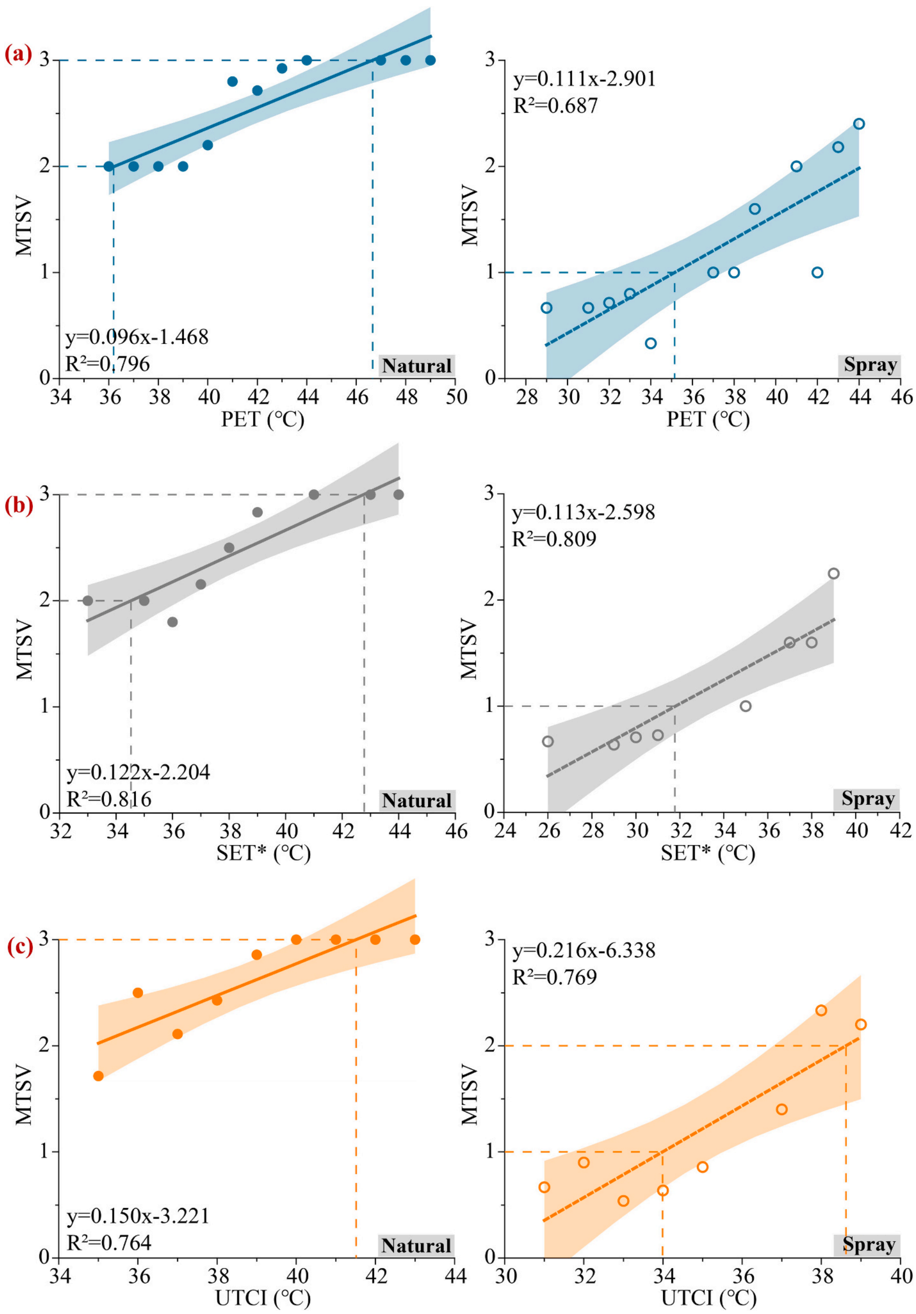

Fig. 10. Regression analysis of thermal sensation and thermal indexes under different cases.

indicating that the increase of T_{sk} would lead to the increase of HSV. This may be related to the decrease of human heat dissipation efficiency caused by the increase of water vapor content in the air.

3.5. Thermal index and thermal response

3.5.1. Thermal indexes and thermal sensation

The thermal indexes PET, SET* and UTCI were calculated by RayMan Pro software. Referring to the research method of Lin et al. (Lin, 2009), the TSV value corresponding to each 1 °C PET, SET* and UTCI interval were averaged, and then the obtained mean thermal sensation vote (MTSV) value and its corresponding PET, SET* and UTCI values were subjected to regression analysis. The regression equation was solved to establish the relationship between MTSV and each thermal comfort index, as shown in Fig. 10. The results showed that there was a strong linear relationship between MTSV and thermal comfort indexes in both natural and spray space. All slopes of the regression model were positive, indicating that MTSV increased with the increase of thermal comfort index. In the natural space, the slope of UTCI was the highest, which was 0.150, the slope of PET was the lowest, which was 0.096, and the slope of SET* was between the two, which was 0.122. In the spray space, the slope of UTCI was the highest, which was 0.216, the slope of PET was the lowest, which was 0.111, and the slope of SET* was between the two, which was 0.113. This showed that MTSV was the most sensitive to the change of UTCI in both natural and spray space, and the sensitivity in spray space was higher than that in natural. For the fitting degree, the R^2 value of SET* was the highest in the natural or spray space.

3.5.2. Thermal indexes and thermal unacceptability

ASHRAE 55–2017 (ASHRAE, ASHRAE Standard 55–2017, 2017) defines the thermal acceptable range (normal conditions) as the temperature range that 80 % of residents can accept, which means that 20 % of residents think that the current thermal environment cannot be accepted. In this study, the thermal unacceptable ratio of subjects corresponding to each 1 °C PET, SET*, and UTCI interval group was calculated, as shown in Fig. 11. The results showed that there was a strong linear relationship between thermal unacceptability and thermal comfort index, and the slopes of all regression models were positive. With the increase of thermal comfort index value, the percentage of thermal unacceptability increased. The slope value of UTCI was the largest in both natural and spray space, suggesting that the thermal unacceptable percentage was sensitive to the change of UTCI. In addition, due to the strong solar radiation, harsh temperature and humidity environment, when the subjects were directly exposed to the nature, the thermal unacceptable percentage was much higher than 20 %, while in the spray space, the thermal acceptable rate was greatly improved.

3.6. Heat stress scale correction of thermal comfort index

3.6.1. Modification based on thermal sensation regression

In order to accurately evaluate the outdoor thermal environment, the thermal comfort indexes PET, SET* and UTCI values exposed to natural and spray space were determined on the basis of experimental measurement and questionnaire survey, as shown in Tables 8 and 9. Since the experiment was carried out in hot summer and the spray system was only used for urban cooling, the MTSV was higher than 0, and the thermal perception level only included 0, +1, +2, +3.

Table 8 compares the original thermal stress of the thermal comfort index with the modified thermal stress in the natural space in Qingdao. It can be seen that within the same thermal sensation range, the modified thermal index value was lower than or close to the original thermal index value. With the increase of thermal perception scale, the modified value was closer to the original value. This may be due to Qingdao's marine climate, making it cooler in summer all year round, while the human body's physiological adaptability to the hot climate was poor.

Table 9 compares the original thermal stress of the thermal comfort index and the modified thermal stress in the spray in Qingdao. It was found that the modified thermal index value in the spray was significantly higher than the original thermal index value in the same thermal sensation range compared with sunlight. For example, the moderate heat stress range of 34–38 °C in the UTCI index of this study was much higher than the original thermal stress range of 26–32 °C and the modified thermal stress range of 28–34 °C in the natural space, indicating that the human body could withstand higher temperatures in the spray space, which may be due to the fact that the spray environment improved the heat tolerance of the human body. In addition, the modified PET range was the widest and the UTCI range was the narrowest in Tables 8 and 9, which was consistent with the finding of Oh et al. (2019) that the PET thermal index showed the widest range and the WBGT showed the narrowest range in the spray space.

3.6.2. Modification based on thermal unacceptable percentage

In addition to using thermal sensation voting to correct the evaluation scale of thermal comfort index, the thermal stress range can also be modified by the thermal unacceptable percentage. The thermal sensation was also divided into four thermal perception scales. Previous studies have divided the 80 % thermal acceptability of the thermal stress range into four parts on average (Pantavou et al., 2013). In this study, the range of 0 % ~ 20 % thermal comfort index value was divided into no heat stress and thermal sensation was 0. The range of 20–46.67 % thermal comfort index value was divided into moderate heat stress, and the thermal sensation was +1. The thermal comfort index value range of 46.67 % ~ 73.34 % was divided into moderate heat stress, and the thermal sensation was +2. The range of 73.34 % ~ 100 % thermal comfort index value was divided into strong heat stress and the thermal sensation was +3.

Tables 10 and 11 show the correction range of thermal comfort index scale in the natural and spray space, respectively. Compared with the original thermal comfort index scale and the correction scale based on the thermal sensation regression prediction method, the correction range of thermal comfort index scale based on the thermal unacceptable percentage was higher than the two in both

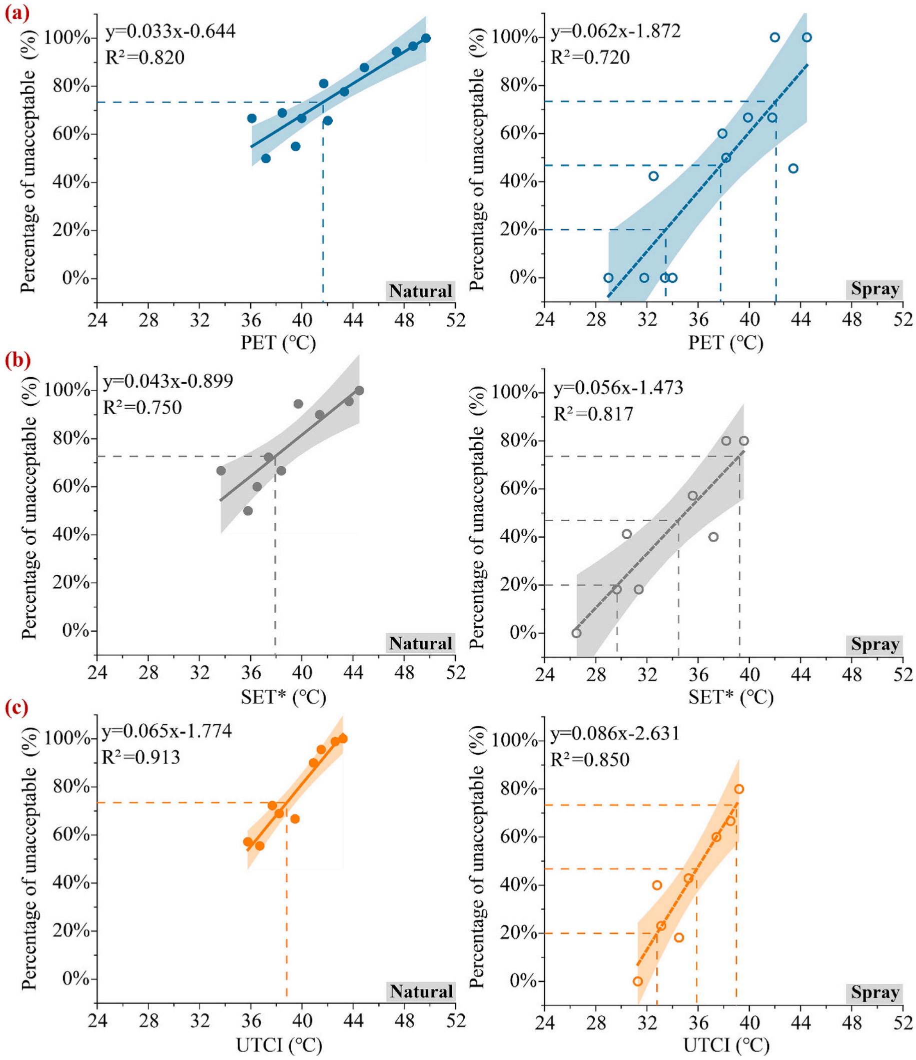

Fig. 11. Regression analysis of thermal unacceptable percentage and thermal indexes under different cases.

Table 8
Scale correction of thermal comfort index in the natural space based on thermal sensation regression.

Thermal perception	Comfort scale	Stress category	TSV scale	Original PET (°C)	Modified PET (°C)	Original SET* (°C)	Modified SET* (°C)	Original UTCI (°C)	Modified UTCI (°C)
Hot	Very uncomfortable	Strong heat stress	+3	>35	>36	>34	>34	>32	>34
Warm	Uncomfortable	Moderate heat stress	+2	29–35	25–36	30–34	26–34	26–32	28–34
Slightly warm	Slightly uncomfortable	Slight heat stress	+1	23–29	15–25	~	18–26	~	21–28
Neutral	Comfortable	No thermal stress	0	18–23	5–15	17–30	10–18	9–26	15–21

natural and spray space. However, both methods showed that the modified PET range was the widest and the UTCI range was the narrowest. By comparing the stress range of each thermal index in Tables 10 and 11, it can be found that the thermal stress range of the modified indexes in the natural space was wider than the original thermal stress range, while it was narrower in the spray space, indicating that the spray space was more susceptible to microclimatic fluctuations when judging thermal sensation with the thermal index range formed by thermal unacceptability.

Table 9
Scale correction of thermal comfort index in the spray space based on thermal sensation regression.

Thermal perception	Comfort scale	Stress category	TSV scale	Original PET (°C)	Modified PET (°C)	Original SET* (°C)	Modified SET* (°C)	Original UTCI (°C)	Modified UTCI (°C)
Hot	Very uncomfortable	Strong heat stress	+3	>35	>44	>34	>41	>32	>38
Warm	Uncomfortable	Moderate heat stress	+2	29–35	35–44	30–34	32–41	26–32	34–38
Slightly warm	Slightly uncomfortable	Slight heat stress	+1	23–29	26–35	~	23–32	~	29–34
Neutral	Comfortable	No thermal stress	0	18–23	17–26	17–30	14–23	9–26	25–29

Table 10
Scale correction of thermal sensation index in the natural space based on thermal unacceptable percentage.

Thermal perception	Comfort scale	Stress category	TSV scale	Original PET (°C)	Modified PET (°C)	Original SET* (°C)	Modified SET* (°C)	Original UTCI (°C)	Modified UTCI (°C)
Hot	Very uncomfortable	Strong heat stress	3	>35	>41	>34	>37	>32	>38
Warm	Uncomfortable	Moderate heat stress	2	29–35	33–41	30–34	31–37	26–32	34–38
Slightly warm	Slightly uncomfortable	Slight heat stress	1	23–29	25–33	~	25–31	~	30–34
Neutral	Comfortable	No thermal stress	0	18–23	19–25	17–30	21–25	9–26	27–30

Table 11
Scale correction of thermal sensation index in the spray space based on thermal unacceptable percentage.

Thermal perception	Comfort scale	Stress category	TSV scale	Original PET (°C)	Modified PET (°C)	Original SET* (°C)	Modified SET* (°C)	Original UTCI (°C)	Modified UTCI (°C)
Hot	Very uncomfortable	Strong heat stress	3	>35	>42	>34	>39	>32	>39
Warm	Uncomfortable	Moderate heat stress	2	29–35	37–42	30–34	34–39	26–32	36–39
Slightly warm	Slightly uncomfortable	Slight heat stress	1	23–29	33–37	~	29–34	~	33–36
Neutral	Comfortable	No thermal stress	0	18–23	30–33	17–30	26–29	9–26	30–33

3.6.3. Comparison of thermal sensation prediction accuracy

The original heat stress scale, the heat stress correction scale of each thermal comfort index based on the thermal sensation regression and thermal unacceptable percentage analysis method were verified with the thermal comfort index value and the thermal sensation vote obtained from the experiment. The correct prediction percentage of thermal sensation was calculated, as shown in Table 12. The results showed that the thermal sensation correction scale based on thermal sensation regression analysis and thermal unacceptable percentage analysis was higher than the original thermal stress scale for the prediction of thermal sensation. The correction scale calculated by thermal unacceptable percentage analysis method had the highest prediction accuracy for thermal sensation in the natural space, while the prediction accuracy calculated by thermal sensation regression method was the highest in the spray. These two methods were 22.76 % and 41.33 % higher than the original thermal stress scale prediction accuracy, respectively. The prediction performance of UTCI was excellent in the natural space, and the prediction accuracy was 88 %, while the prediction performance of SET* was excellent in the spray, and the prediction accuracy was 60 %. Oh et al. (2019) found that compared with PET, WBGT, UTCI, SET* was more suitable for evaluating TSV in spray space, which was consistent with the conclusion of this study. However, only using the basic environmental parameters to evaluate the water mist environment would underestimate the cooling

Table 12
Percentage of correct prediction of thermal sensation in different scales of thermal comfort index.

Thermal index calibration method	Natural			Spray		
	PET	SET*	UTCI	PET	SET*	UTCI
Original thermal stress prediction	60.00 %	62.86 %	60.00 %	6.67 %	29.33 %	6.67 %
Thermal sensation regression prediction	65.33 %	65.33 %	62.67 %	**58.67 %**	**60.00 %**	**48.00 %**
Thermal unacceptable percentage prediction	**87.14 %**	**76.00 %**	**88.00 %**	34.67 %	48.00 %	42.67 %

effect of the water mist spray device. When the UTCI value in the sunlight exceeded 38 °C, the region reached the range of strong heat stress. It was necessary to start the spray device to improve the thermal environment. When the SET* value in the spray exceeded 41 °C, the spray still cannot improve the thermal health status of the human body, and it was recommended to reduce the corresponding outdoor activities.

4. Limitations and further work

The subjects involved in the experiment are all students in school. Their age, educational background and social experience are relatively homogeneous. Although it is helpful to control the experimental conditions and improve the efficiency, whether the research results can be directly applied to a wider range of social groups and environment should also be explored. In addition, the measurement of the thermal environment in the spray field should increase the measuring points in each dimension, and the number of measuring points for skin temperature should also be increased to improve the accuracy of the evaluation.

In terms of thermal stress index modification, only the correlation between thermal stress index and thermal sensation under different environments is considered, and the influence of time is ignored. In view of the real situation simulation of pedestrian outdoor activities, it is impossible to effectively identify the length of pedestrian activity time for the embedded program of the spray system. Therefore, the data from 1 to 15 min are calculated and analyzed in order to better control the operation of the spray system. In fact, the time spent in the spray will significantly affect the subjective perception. For example, the modified thermal index value after staying in the spray for 1 min or 10 min may be quite different. In the future, it is necessary to explore the correlation between the thermal stress index of the time series and the thermal sensation.

Due to the limitation of experimental conditions, the effect of additional heat loss caused by the evaporation of spray on the skin surface on thermal sensation is not explored. In the future, it is necessary to comprehensively consider the changes of convection and radiation heat transfer caused by v_a, T_a and G, as well as the variations of evaporation and heat dissipation caused by water mist evaporation and sweating. On the basis of clarifying the variations of boundary conditions, a multi-node thermal regulation model of human body in spray space should be established to predict the changes of thermal sensation and thermal comfort, so as to realize the real-time regulation of spray operation program.

5. Conclusion

In this study, the thermal response of 16 subjects walking for 15 min in the natural and spray space was evaluated. The corresponding heat stress scale of thermal comfort index was modified and the prediction accuracy was calculated by associating thermal sensation and thermal unacceptability. The main conclusions are as follows:

(1) Spray could reduce the outdoor T_a by 2.01 °C and increase the RH by 9.08 % on average, respectively.
(2) Within 15 min of natural space, MTSV increased by 0.73, MTCV decreased by 1.13, MHSV decreased by 0.80. Within 15 min of spraying, MTSV decreased by 1.07, MTCV increased by 0.80, and MHSV increased by 1.27.
(3) The T_{sk} rise rate of 0–5 min in the natural space was about twice that of 5–10 min. The T_{sk} increased in 0–10 min in the spray, and decreased in 10–15 min. T_{Arm} decreased the most significantly, which was 0.23 °C.
(4) MTSV was the most sensitive to the change of UTCI in both natural and spray space, and the sensitivity in the spray was higher than that in the natural space. For the degree of fitting, the R^2 value of SET* was the highest in the natural space ($R^2 = 0.816$) or spray ($R^2 = 0.809$).
(5) When predicting the thermal sensation in the natural environment, the thermal unacceptable percentage can be used for prediction, and the UTCI prediction accuracy (88 %) was the highest. When predicting the thermal sensation in the spray, the thermal sensation regression prediction can be used, and the SET* prediction accuracy (60 %) was the highest.
(6) When the UTCI exceeded 38 °C in Qingdao, the outdoor heat risk reached the range of strong heat stress, and it was necessary to start the spray device to improve the thermal environment. When the SET* in the spray exceeded 41 °C, the spray still cannot improve the thermal health status, and it was recommended to reduce outdoor activities.

CRediT authorship contribution statement

Yi Gao: Methodology, Formal analysis, Investigation, Writing – review & editing. **Liming Ge:** Resources, Formal analysis. **Xi Meng:** Investigation, Supervision, Writing – review & editing.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work. And there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Data availability

Data will be made available on request.

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