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Thermal Pleasure–Based Spacing of Mist–Shade Umbrellas in Hot–Humid Outdoor Walkways Using an Extended JOS-3

Model

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ABSTRACT

Studies on pedestrian thermal pleasure (TP) in summer have mainly focused on the instantaneous cooling effects of microclimate-regulation facilities. However, to enable rational planning of microclimate-regulation facilities, the dynamics of TP during the post-cooling walking process remains insufficiently understood. This study conducted field experiments along a landscape walkway in Guangzhou, China, to examine how mist–shade umbrella (MsU) affect the induction and dissipation of TP under hot–humid subtropical conditions. The results showed that MsU exposure significantly improved the pedestrian-level thermal environment, reducing UTCI by 6.1 °C relative to the sun-exposed section and by 1.2 °C relative to the tree-shaded section. Regardless of prior thermal exposure, entering the MsU induced TP with comparable intensity. However, after leaving MsU, TP dissipation was strongly governed by subsequent thermal exposure, decaying rapidly under sun exposure (–35%) but much more slowly under tree-shaded conditions (–3%). Further analysis indicate that both instantaneous TP and its cumulative dissipation are significantly associated with upper-body skin temperatures and accumulated heat load of the body. Using the back-skin-temperature threshold (34.9 °C) and an extended JOS-3 simulation, TP was sustained for 28 min under the shade-recovery conditions (UTCI = 38.5 °C), implying a cooling-point spacing of 1.4 km, providing quantitative evidence for planning of MsU along hot–humid landscape walkways.

Keywords: Thermal Pleasure; Landscape walkway; Misting Cooling; JOS-3; Skin Temperature; Adaptive Thermal Comfort

1. Introduction

Regarding public health risk reduction, walking in urban green spaces has shown clear benefits at both the psychological (Hu et al., 2025) and physiological (Hvid et al., 2025) levels. In hot–humid climates, however, frequent heat extremes substantially diminish the summer attractiveness of landscaped pedestrian walkways. Notably, nature-based solutions such as tree shade can markedly reduce pedestrian-scale T_{mrt} and associated heat-stress risks (Nevers et al., 2026; Wei et al., 2025). Yet survey evidence indicates that, even under tree shade, daytime Physiological Equivalent Temperature in subtropical urban parks can still reach 39.3 °C (Li, et al., 2024), far above the range preferred by visitors (20.9–28.4 °C). Collectively, these findings suggest that relying solely on nature-based measures is insufficient to sustain the environmental appeal of walking spaces in hot-humid regions, and that thermal-environment regulation strategies for outdoor walkways should be re-examined from the perspective of pedestrians' real walking processes.

To enhance the attractiveness of outdoor walkways, microclimate-regulation facilities have been introduced into hot–humid outdoor environments to address pedestrians' primary complaints—excessive radiant load and high T_a (Li et al., 2024). Existing strategies include shading canopies, water-mist systems (Kyogoku and Takebayashi, 2023; Taleghani, 2018; Taleghani and Berardi, 2018), localized airflow delivery, pavement evaporative cooling, membrane-assisted radiant cooling (Yang et al., 2024), and passive radiative sky-cooling materials (De Masi et al., 2026; Su et al., 2025). These technologies operate through different heat-transfer pathways: shading reduces shortwave radiant load, misting enhances evaporative cooling, membrane-assisted radiant cooling modifies long-wave radiative exchange between the human body and cooled panels, and passive radiative sky-cooling materials reduce surface heat gain through high solar reflectance and thermal emittance.

Among these, combined cooling facilities have received increasing attention. The combination of misting and shading is particularly promising because it can simultaneously attenuate solar radiation and enhance evaporative heat loss (Ulpiani and Zinzi, 2023). Recent studies have shown that mist-spray systems can improve short-term thermal sensation and comfort in outdoor premises, while combined shading – misting strategies can achieve stronger improvements in pedestrian thermal environments than misting alone (Li et al., 2026). Reported effects include a 5–7 °C reduction in T_a (Huang et al., 2017) and an approximately 14.4 °C decrease in PET (Zhao et al., 2024). Given that the integration of misting and shading is both practically feasible and thermally beneficial, this study focuses on this combined strategy and further investigates the mechanisms through which it affects pedestrians' thermal perception during outdoor walking.

Nevertheless, existing field and simulation studies have largely focused on local performance metrics of misting systems, such as water flow rate (Di Giuseppe et al., 2021), nozzle height (Su et al., 2022), and nozzle density (Ulpiani, 2019). With respect to the local cooling benefits, prior work has mainly examined environmental changes

and immediate subjective responses during mist operation. In real-world outdoor walking, however, pedestrians move through a sequence of sun-exposed, tree-shaded, and artificially cooled segments, instead of remaining within a single cooled spot. As a result, the effectiveness of a microclimate-regulation facility cannot be understood solely at the device scale, but must be evaluated in relation to the walking route on which natural and artificial cooling opportunities are encountered. This reveals a critical gap in current research: the route-scale role of microclimate-regulation facilities in complementing natural shade along landscape walkways remains unexplored. Consequently, there is still no clear planning basis for where, how, and at what intervals MsUs should be deployed to maintain walking attractiveness and encourage greater use of outdoor walkways.

When pedestrians enter an artificial cooling point, they often encounter abrupt thermal-environment sequences (Xie et al., 2024), with marked short-term changes in T_a , radiant intensity, and evaporative conditions. Such abrupt transitions can readily elicit thermal alliesthesia. Alliesthesia was originally proposed to describe abrupt changes in sensation (Cabanac, 1979). Within adaptive thermal comfort research, this mechanism has been further developed into the concept of TP. Thermal stimuli that are clearly distinct from one's thermal history and can restore the body's toward the thermoneutral range can elicit positive thermal alliesthesia, i.e., TP. TP has been shown to be influenced not only by abrupt thermal transitions but also by prior thermal history (de Dear, 2011; Parkinson and De Dear, 2015). Accordingly, compared with conventional thermal comfort indices, TP is particularly suitable for evaluating corrective thermal stimuli and the resulting walking experience along landscape walkways that include artificial cooling points (Li et al., 2022). Recent studies suggest that TP can be characterized via physiological responses—especially skin temperature and its temporal dynamics—which may capture transient and local features of thermal perception better than composite thermal indices (Belyamani et al., 2024). However, such evidence has primarily been derived from controlled laboratory settings or static exposure conditions (Dzyuban et al., 2022; Liu et al., 2021), while physiological data from real outdoor walking routes remain scarce. Meanwhile, existing multi-node thermophysiological models typically assume that evaporative heat loss is dominated by sweating, and thus struggle to represent the intense localized evaporation induced by surface water films in misting environments—constraining their applicability to mist-cooling scenarios.

In summary, it remains unclear (i) which physiological variables best capture the dynamic evolution of TP in real-world walking scenarios that pass through mist-cooling point, (ii) how long cooling-induced TP persists after leaving the cooling point, and (iii) how these processes can be translated into an appropriate spatial spacing of cooling points along landscape pedestrian walkways. To address these questions, this study conducted a field experiment to systematically analyze the thermal environment, physiological responses, and TP of pedestrians as they enter and leave MsU along landscape walkways in a hot-humid climate. A multi-node thermophysiological model was further extended to represent mist-induced local evaporation and, based on the improved model, estimated an effective spacing of cooling points required to maintain thermal pleasure along outdoor walkways. The main objectives are as follows:

- (1) Experimentally investigate, under hot-humid conditions, the changes in thermal-environment parameters experienced by pedestrians before and after entering a MsU along landscape walkways with different shading conditions, as well as pedestrians' physiological and subjective responses;
- (2) Identify physiological parameters that reflect fluctuations in TP when pedestrians walk through “misting-non-misting” sequences, and determine threshold values for these parameters;
- (3) Extend a multi-node thermophysiological model to account for localized evaporation induced by misting environments and validate the model using field data;
- (4) Estimate the effective spatial interval of MsUs along outdoor walkways required to sustain TP.

2. Methodology

To investigate the persistence of TP induced by a combined mist-shading cooling strategy during walking, this study adopted a two-step design to characterize the thermal environment and physiological responses in different walking conditions and to derive a reasonable spacing for the cooling device. First, participants completed a walking experiment along a landscape walkway loop on clear summer days. Real-time physiological and environmental parameters were continuously monitored, and subjective votes on TP were collected using questionnaires. Second, local skin-temperature dynamics during the post-misting walking period were simulated, and the design spacing of the device was estimated based on the time required for local body regions to reach an unpleasantness threshold.

2.1. Research Site

Guangzhou is located in the south-central part of Guangdong Province, China, on the northern edge of the Pearl River Delta (23°7' N, 113°15' E), and is classified as Cfa under the Köppen climate classification (Peel et al., 2007). The city has hot and humid summers and relatively cool, dry winters. The field experiment was conducted along the lakeside of West Lake on the Wushan Campus of South China University of Technology (SCUT), Tianhe District, Guangzhou, at a university site featuring a typical landscape walkway (Fig. 1a). This lakeside area is commonly used by students for everyday outdoor walking and leisure. The walkway has tree shade on one side and no shade on the other, enabling experiments under contrasting shading conditions (Fig.1b).

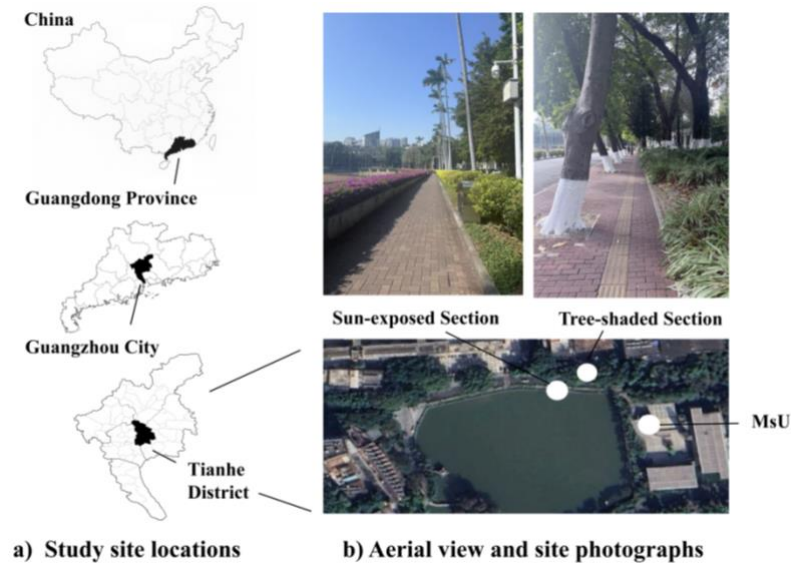


Fig. 1. Location and field scenes of the study site.

The tree-shaded section was mainly planted with *Michelia alba* DC. at an approximate interval of 2.5 m. *Michelia alba* is an evergreen subtropical ornamental tree commonly cultivated in South China and other tropical or subtropical regions. It is generally described as a medium-sized evergreen tree with an upright habit; horticultural references report a typical mature size of approximately 8–12 m in height and 4–6 m in crown width, although much larger old individuals can occur under favorable conditions (Lin et al., 2018). As seen in Fig. 1b, the tree-shaded section should be interpreted as a shaded walkway with possible canopy gaps and partial solar penetration, rather than as a completely opaque overhead shade.

2.2. The mist-shade prototype

Previous studies have identified T_{mrt} as a primary determinant of thermal comfort in walking environments (Nasrollahi et al., 2017; Taleghani, 2018). Evidence related to TP induction further suggests that, under warm conditions, reductions in T_a and decreases in local skin temperature can facilitate the elicitation of TP (Santamouris et al., 2017). Accordingly, a MsU was designed and installed at the experimental site (Fig. 2).

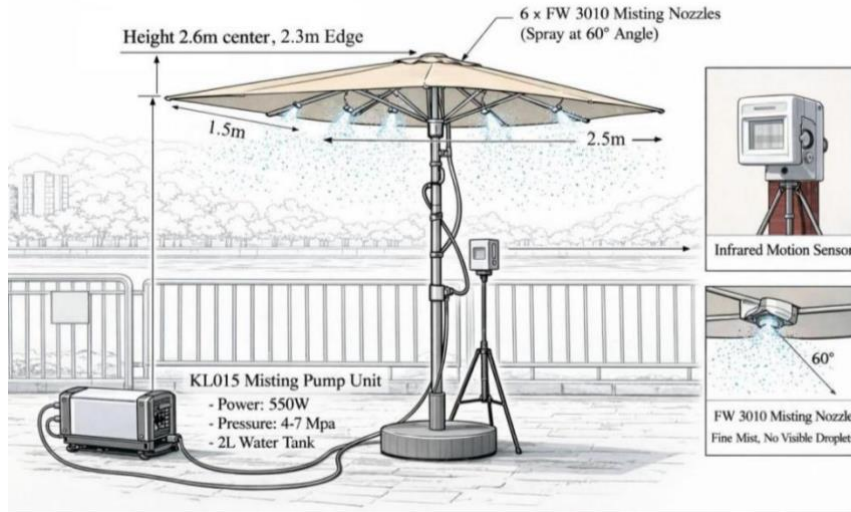


Fig. 2. Schematic of the design and device parameters of the MsU.

To align with the intended one-sided placement along the walkway, the umbrella adopted a half-canopy configuration. The umbrella shaded an area of 2.5 m × 1.5 m. The canopy height was 2.6 m at the apex and approximately 2.3 m along the perimeter (Fig. 2). A high-pressure water line was routed evenly along the ribs on the long edge of the canopy. Six nozzles were installed along the line, with a spacing of approximately 0.5 m between adjacent nozzles. The main supply hose ran down along the umbrella pole and was connected to a high-pressure misting unit (model KL015; rated power 550 W; operating pressure 4-7 MPa) equipped with a 2 L water tank. The nozzles (model FW 3010) generated a fine mist with no noticeable falling droplets. A passive infrared human-presence switch was mounted on a tripod adjacent to the umbrella, supplying power to the misting unit only when a participant approached the MsU. When activated, the nozzles discharged mist at an angle of approximately 60° downward.

2.3. Experimental period, protocol and questionnaire

The measurements of thermal-environment parameters, local skin temperatures of participants, and subjective questionnaires were conducted on five clear-sky days between 3 and 23 August 2025, selected to represent typical summer weather conditions in Guangzhou. On each experimental day, two sessions were scheduled: a morning session (10:00–11:00) and an afternoon session (15:00–16:00), with an equal allocation of trials between the two time windows (morning:afternoon = 1:1).

Before the formal trial, participants changed into standardized experimental clothing in a preparation room (T_a 25.0 °C, RH 70%), where skin-temperature patches were attached. All participants signed an informed consent form and were compensated with a stipend. Participants then remained seated for 30 min to stabilize. After completing the first questionnaire, the outdoor experiment began. The protocol consisted of: (i) 15 min walking along a tree-shaded section; (ii) 10 min standing rest under the MsU; (iii) 15 min walking along a sun-exposed section; (iv) 10 min standing rest under the MsU again; and (v) 10 min walking along the tree-shaded section to finish the trial. The total duration was 60 min. During walking periods, questionnaires were completed every 5

min; during the MsU periods, questionnaires were administered at the 1st, 5th, and 10th min (Fig. 3).

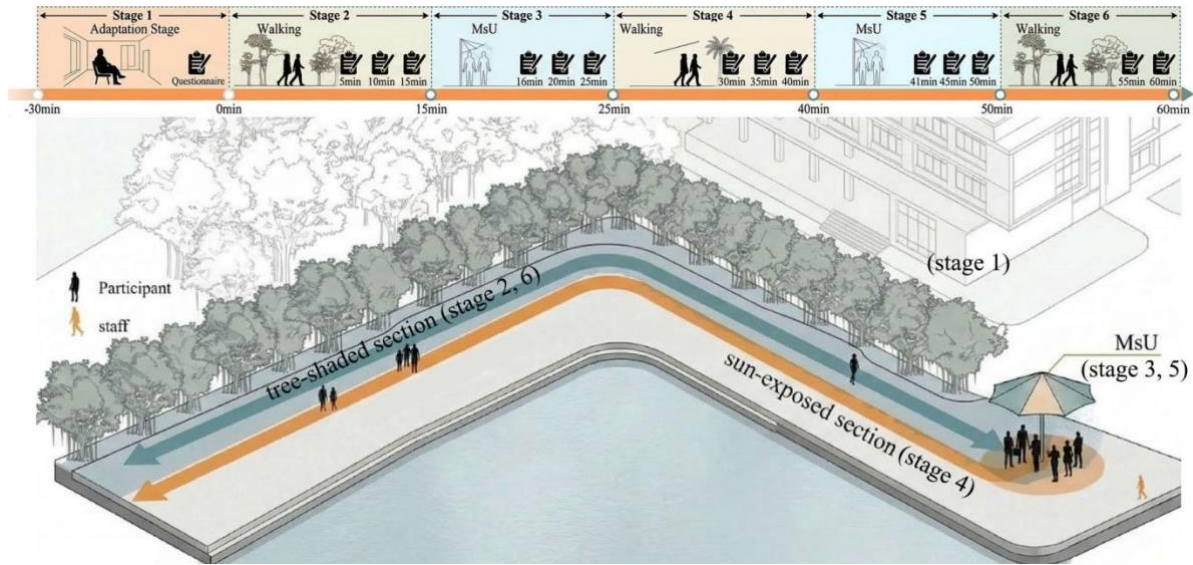


Fig. 3. Experimental stages and survey schedule.

The exposure durations were selected to induce measurable thermal-affective responses under changing outdoor microclimatic conditions while limiting excessive heat strain. The total outdoor protocol was restricted to 1 h for participant safety under hot-humid summer conditions. The 15-min walking period was chosen because previous field evidence from Guangzhou showed that skin temperatures of pedestrians tended to stabilize after approximately 15 min of summer outdoor walking, indicating that this duration was sufficient to establish a non-neutral thermophysiological state (Wu et al., 2025). Another Guangzhou heatwave study indicated that continuous direct solar exposure for more than approximately 10 min may increase pedestrian heat risk (Wu et al., 2024); however, the present experiment was conducted under typical summer rather than heatwave conditions. Therefore, 15 min was considered appropriate for producing non-neutral thermal exposure without intentionally inducing excessive heat risk. The 10-min MsU exposure was selected based on previous mist-cooling evidence showing that 10 min of mist exposure enabled more than 90% of participants to reach an acceptable thermal comfort level in outdoor premises (S. Li et al., 2026). Thus, the 10-min MsU period was considered sufficient to capture the primary short-term perceptual and physiological cooling effects while remaining realistic for an outdoor cooling point.

To collect subjective thermal responses during walking under changing microclimatic conditions, both the Thermal Sensation Vote (TSV) and the Thermal Pleasure Vote (TPV) were recorded using continuous sliding scales in the questionnaire. Participants were asked to respond to the TSV question, “What is your perception of the thermal environment now?”, and the TPV question, “How does the current thermal environment affect your emotion at this moment?” by selecting an integer value on a slider ranging from -50 to +50. For TPV, the -50, 0, and +50 points on the slider were labelled as “extremely unpleasant”, “indifferent”, and “extremely pleasant”, respectively. For TSV, the corresponding slider anchors were labelled as “cold”, “neutral”, and “hot”, respectively.

2.4. Participants

Given the experimental protocol, the aim was to examine how a fixed-form mist-shading intervention affected TP across different time periods. The main trial lasted 60 min, each participant provided subjective ratings at 15 time points. This design corresponds to a typical within-subject repeated-measures model: all participants experienced the same protocol and all measurement occasions, with time as the independent variable and TPV as the dependent variable.

To estimate the required sample size, G*Power 3.1 (Faul et al., 2007) was used with the statistical test set to F tests - ANOVA: Repeated measures, within factors. The significance level was set to $\alpha = 0.05$, and statistical power to $1 - \beta = 0.80$. Following Cohen's conventions and the effect-size range reported in previous misting-related studies, a medium effect size of $f = 0.25$ was adopted (Cohen, 2013). Considering a moderate correlation among repeated measurements within the same participant, the correlation among repeated measures was set to $\rho = 0.5$, and the nonsphericity correction was set to $\epsilon = 0.75$ to account for potential violation of the sphericity assumption. Under these assumptions, the initial calculation indicated that a minimum of 14 participants would be required. (Girden, 1992).

Considering the uncontrollable nature of outdoor field experiments, including potential missing observations, participant withdrawal, sensor malfunction, and short-term environmental fluctuations, the recruitment target was increased to 20 participants. To further evaluate the robustness of this sample-size justification, an additional sensitivity analysis was conducted for the planned sample size of 20 participants by varying the key input parameters of the repeated-measures power analysis. The correlation among repeated measurements was varied as $\rho = 0.30$, 0.50 , and 0.70 ; the nonsphericity correction was varied as $\epsilon = 0.50$, 0.75 , and 1.00 ; and Cohen's effect size was varied as $f = 0.10$, 0.25 , and 0.40 , corresponding to small, medium, and large effects. The achieved power ranged from 0.103 to 0.254 for small effects, from 0.427 to 0.960 for medium effects, and from 0.837 to 0.999 for large effects. These results indicate that the planned sample size of 20 participants provided sufficient power for detecting large within-subject effects and acceptable power for medium effects under moderate-to-favorable assumptions, while its ability to detect small effects was limited. Accordingly, the final recruitment target was set at 20 participants (10 males and 10 females). To minimize the influence of long-term thermal history, all participants had lived in Guangzhou for at least 1 year. Participant characteristics are summarized in Table 1.

Table 1. The background information of participants.

Individual factors	Gender	Mean	Min	Max	Std
Age	M	27.80	24.00	34.00	2.90
	F	24.30	18.00	29.00	3.83
Height/cm	M	1.76	1.63	1.87	0.07
	F	1.61	1.50	1.70	0.06
Weight/kg	M	78.50	62.50	100.00	14.42
	F	51.09	28.90	65.00	10.40

Following ISO 8996, participants wore standardized clothing provided by the research team (grey short-sleeved T-shirt, shorts, short socks, and athletic shoes), with a total clothing insulation (I_{cl}) of approximately 0.35 clo. Standing under the MsU corresponded to a metabolic rate of approximately 1.2 met. During walking, the speed was approximately 3.0 km/h, corresponding to a metabolic rate of approximately 2.6 met (ISO 8996, 2005).

2.5 Measurement

To capture both the thermal-environment characteristics experienced by pedestrians and their TP level, this study combined fixed and mobile monitoring platforms equipped with multiple sensors, together with repeated subjective questionnaires.

2.5.1 Fixed monitoring

To characterize the thermal environment at standing height under the MsU, a HOBO MX2302 temperature–humidity data logger was mounted at 1.7 m on the umbrella pole to record T_a and RH, and a Delta OHM HD 32.3 heat-stress meter was installed at the same height to record globe temperature (T_g). An ultrasonic anemometer (Delta HD 52.3D) was also deployed at 1.7 m to measure air velocity (V_a). The accuracy and measurement ranges of all instruments met the requirements of ISO 7726; instrument specifications are listed in Table 2. The layout and photograph of fixed monitoring station are shown in Fig. 4a, c.

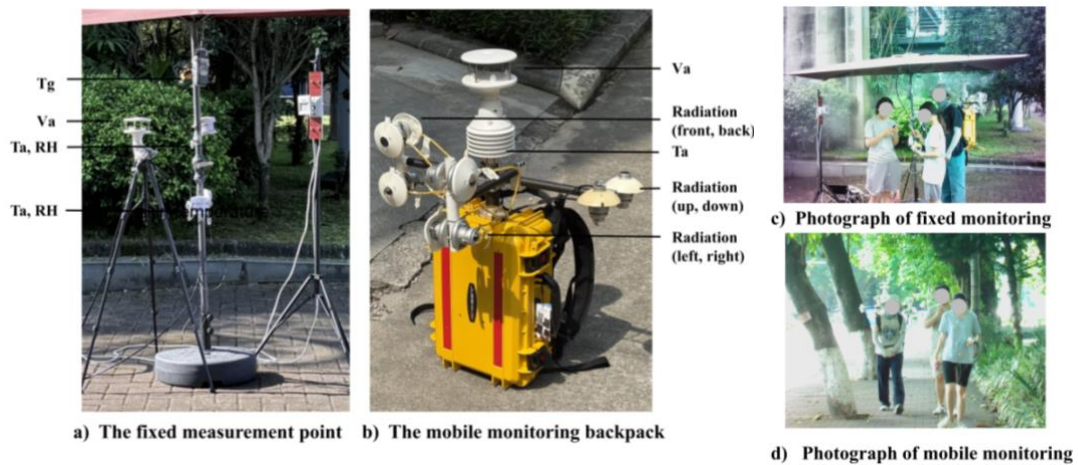


Fig. 4. Measurement equipment used in the field experiment.

2.5.2 Mobile monitoring

To measure pedestrian-scale thermal-environment parameters (Gallacher and Boehnke, 2025), a mobile microclimate monitoring backpack was designed and assembled (Fig. 4b). The monitored variables included six-direction shortwave and longwave radiant flux densities, air velocity (V_a) and wind direction, T_a , and relative humidity (RH). All sensor outputs from the mobile monitoring backpack were recorded by a Campbell CR1000 data logger at 10 s intervals. The photograph of testing with the mobile monitoring backpack is shown in Fig. 4d.

Local skin temperature was measured using a four-channel thermocouple temperature logger. The accuracy and measurement range of all sensors complied with ISO 7726 (ISO 7726:1998(E), 1998). Detailed specifications are provided in Table 2.

Table 2 Field test instrument probe information

Platform	Measured variable	Instrument model	Measurement range	Accuracy
Fixed monitoring point	T _a	HOBO MX2302	-40~60 °C	± 0.15 °C
	RH		0~100 %	0.1 %
	T _g	Delta OHM HD32.3	-10~100 °C	± 0.05 °C
	V _a	Delta-HD52.3D	0~60m/s	±0.2 %
Mobile monitoring station	Radiant flux density	Kipp&Zonen-CGR3	-250~250W/m ²	<1 %
		Kipp&Zonen-CMP3	-250~250 W/m ² (4.5~42 μm)	<1 %
		Hukseflux-NR01	0~200 W/m ² (0.3~2.8 μm)	<1 %
			-250~250 W/m ² (2.5~42 μm)	<1 %
	T _a		-40~60 °C	±0.15 °C
	RH	Delta-HD52.3DP147	0~100 %	0.1 %
	V _a		0~60m/s	±0.2 %
	Local skin temperature	UX120-014M	-20~70 °C	± 0.21 °C

2.6 Data analysis

2.6.1 Calculation of the T_{mrt}

T_{mrt} was determined separately from the T_g at the fixed measurement point and from the six-direction radiative fluxes measured by the mobile monitoring backpack. For the six-direction shortwave and longwave radiometers, readings were temperature-corrected prior to calculating T_{mrt}. Let the six-direction shortwave irradiances be K_i (i = up, down, front, back, left, right), the longwave irradiances be L_i , and the directional weighting factors be F_i . The total radiant flux density absorbed by the human body, S_{str} , can be expressed as Eq. (1) (“VDI 3787 Blatt 2 - 2008-11 - DIN Media,” n.d.). Here, α_k is the shortwave absorptivity of the human body (set to 0.70), ε_p is the longwave emissivity of the human body (set to 0.97), and the weighting factors satisfy $\sum F_i = 1$. The typical values used were 0.06 for the upward direction, 0.06 for the downward direction, and 0.22 for each of the four horizontal directions (Thorsson et al., 2007).

$$S_{str} = \sum_{i=1}^6 F_i (\alpha_k K_i + \varepsilon_p L_i) \quad (1)$$

T_{mrt} around the walking participants was then determined using Eq. (2), where $\sigma = 5.67 \times 10^{-8} \text{Wm}^{-2}\text{K}^{-4}$ is the Stefan–Boltzmann constant and the result is reported in °C. In terms of temporal processing, S_{str} was first computed for each 10-s sample, and then averaged within each 1-min window. The 1-min mean S_{str} was subsequently used to back-calculate T_{mrt} at the 1-min scale, to avoid bias introduced by the non-linear fourth-power relationship (Taleghani, 2018).

$$T_{mrt} = \left(\frac{S_{str}}{\varepsilon_{p\sigma}} \right)^{1/4} - 273.15 \quad (2)$$

For the fixed measurement point, based on T_a , T_g , and V_a recorded, T_{mrt} around the participants standing under the MsU was calculated using Eq. (3).

$$T_{mrt} = \left[\left(T_g + 273.15 \right)^4 + \frac{1.10 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} \left(T_g - T_a \right) \right]^{1/4} - 273.15 \quad (3)$$

2.6.2 Integrated thermal indices

To comprehensively evaluate the pedestrian-scale thermal environment created by the MsU, this study used UTCI (Universal Thermal Climate Index) and PET as assessment indicators. UTCI was developed for complex outdoor microclimates involving walking pedestrians; it integrates T_a , RH, V_a , and T_{mrt} , and converts ambient conditions into an equivalent temperature representing whole-body heat stress based on the Fiala multi-node thermoregulation model (Jendritzky et al., 2012). PET originates from the Munich Energy-balance Model for Individuals (Höppe, 1999) and is highly sensitive to variations in T_{mrt} , making it effective for reflecting cooling effects associated with shading and radiative-load reduction. The use of UTCI and PET has been widely adopted for thermal-environment analyses in outdoor thermal environment.

Using participants' height and weight, the mobile monitoring data (radiation, T_a , RH, V_a), and the measurements at 1.7 m under the MsU (T_a , RH, T_g), UTCI and PET were computed for the entire experimental period (Bröde et al., 2012).

2.6.3 Statistical and regression analysis

All statistical analysis were conducted in SPSS v26.0. Paired-sample and independent-sample t-tests were used to examine differences between groups, and Pearson correlation analysis was applied to test for significant associations. Statistical significance was evaluated using p-values, with $p < 0.05$ indicating significance and $p > 0.05$ indicating non-significance.

Thermal pleasure decay (TPV_decay) was defined as the net change in TPV during a given walking section following exposure to a cooling point. TPV_decay was calculated as the difference between the TPV recorded at the end of the subsequent walking section and the TPV recorded immediately after leaving the cooling point:

$$TPV_decay = TPV_{end} - TPV_{start} \quad (4)$$

where TPV_{start} denotes the TPV at the end of misting exposure, and TPV_{end} denotes the TPV at the end of the subsequent walking stage. A negative TPV_{decay} indicates a net loss of TP, whereas a positive value indicates that TP was maintained or further accumulated. This stage-based metric was used to quantify the dissipation of cooling-induced pleasure.

To examine the relationship between TP and local skin temperature, weighted linear regression was employed for two reasons. First, the number of observations was markedly uneven across different skin-temperature ranges during the experiment; applying weights allows temperature intervals with larger sample sizes and higher

statistical reliability to contribute more appropriately to model fitting. Second, local skin temperatures were binned using 0.5 °C intervals, and the mean TPV within each bin was calculated to reduce the influence of transient individual fluctuations, thereby enabling the regression model to better reflect the overall trend.

2.7 Extended JOS-3 model

To simulate the minute-scale dynamics of local skin temperature after misting exposure, this study employed the JOS-3 thermophysiological model (Japanese Outdoor Standard Model, version 3) (Tanabe et al., 2002). JOS-3 represents the human body using one core compartment and 17 skin segments, and predicts the transient responses of core and local skin temperatures by coupling heat balance processes, including convection, radiation, respiration, evaporation, and tissue conduction, with active and passive thermoregulatory control. The model has been widely applied in studies of outdoor heat exposure and thermal comfort.

In the original JOS-3 framework, evaporative heat loss is primarily represented as an endogenous sweating process driven by the interaction between sweat production and the ambient evaporative potential. Under misting-induced wet exposure, however, additional evaporative heat loss may occur when mist droplets adhere to the skin or clothing surface. Oh et al. referred to this process as mist wettedness, namely the evaporative heat loss caused by mist droplets wetting the body surface (Oh et al., 2020). In related modelling work, mist wettedness was further defined as the ratio of the actual evaporative heat loss caused by mist droplets to the maximum available evaporative heat loss on the body surface under the same environmental conditions. This concept is therefore different from ambient humidity alone and also differs from the standard sweat-related skin wettedness in thermoregulation models; it represents an exogenous water-induced evaporative pathway associated with mist deposition.

Under the MsU condition, the original JOS-3 model cannot explicitly represent the enhanced evaporation from a residual water film that persists after misting stops, nor the gradual decay of this cooling effect as the surface dries. As a result, the slow rebound of skin temperature observed after leaving the MsU—linked to the cool and humid exposure under the umbrella—cannot be fully reproduced by the original model.

To address this limitation, following the mist-wettedness concept proposed by Oh et al., an exogenous water-film evaporation term was introduced into the JOS-3 evaporation module. This additional evaporative flux (“segment mask”) was applied only to the upper-body segments substantially affected by misting, namely the forehead, shoulders, chest, back, arms, and hands, while the remaining segments retained the original model structure.

2.7.1 Principle of extension

The surface wetness at the moment misting ended was described by the water-film coverage ratio, $\omega(t)$, and was assumed to decay exponentially over time:

$$\omega(t) = \omega_0 \exp\left(-\frac{t}{\tau}\right) \quad (5)$$

where ω_0 is the initial water-film coverage ratio at the end of misting, and τ is the drying time constant (min). The corresponding exogenous water-film evaporative heat flux is defined as:

$$E_{mist,i}(t) = \omega(t) \square E_{max,i} \quad (6)$$

where $E_{max,i}$ denotes the maximum evaporative capacity (W/m^2) of segment (i) under the current environmental and clothing conditions, as calculated internally by JOS-3 from the local vapor-pressure gradient, aerodynamic conditions, and clothing resistance. This formulation allows exogenous water-film evaporation to be represented in parallel with the original sweat-evaporation pathway without altering the overall thermoregulatory framework.

2.7.2 Parameter estimation and validation

To estimate the mist-induced water-film parameters under the experimental conditions, participant-specific parameter inversion was performed using the field measurements. Two parameters were estimated: the initial external water-film coverage ω_0 and drying time constant τ .

First, the model state at the end of the MsU phase (minute 50 of the protocol) was aligned with the measured thermal state. Under the boundary conditions measured beneath the MsU during minutes 50 (T_a , T_{mrt} , RH , and V_a), the model was iteratively preconditioned. Preconditioning continued until the difference between the simulated mean skin temperature and the mean skin temperature derived from the measured local skin temperatures (ISO 9886 (E), 2004) across the monitored sites was within ± 0.1 °C, or until the maximum number of iterations was reached. This procedure provided a consistent initial body-temperature field for the post-misting simulation.

Next, the model was driven by the measured minuted-level environmental inputs during the 10 min tree-shaded walking (minute 51 – 60 of the full protocol). A grid search over ω_0 (range 0–1, step 0.02) and τ (range 2–30 min, step 0.5 min) was carried out for each participant. $51 \times 57 = 2907$ candidate parameter combinations (ω_0, τ) were evaluated for each participant.

For each parameter combination, the model was reset to the same aligned minute-50 body-temperature field. The mist-induced water-film term was then activated on the predefined mist-affected body segments, and the model was run for 10 minutes using the measured environmental inputs. The fitted skin-temperature sites were Back, Shoulder, and hand. The shoulder and hand temperatures were calculated as the averages of the left and right corresponding JOS-3 body segments. For each candidate parameter pair, the simulated local skin temperatures were compared with the corresponding measured values, and the overall root-mean-square error (RMSE) was used as the objective function (Chai and Draxler, 2014):

$$RMSE(\omega_0, \tau) = \sqrt{\frac{1}{3N} \sum_{t=1}^N \left[\left(T_{back,sim,t} - T_{back,obs,t} \right)^2 + \left(T_{shoulder,sim,t} - T_{shoulder,obs,t} \right)^2 + \left(T_{hand,sim,t} - T_{hand,obs,t} \right)^2 \right]} \quad (7)$$

where $N=10$ for the minute-level calibration. The parameter pair that minimized the RMSE was selected as the optimal participant-specific estimate.

To improve transparency and reproducibility, a step-by-step example of the grid-search calibration procedure is provided in Appendix 1. Participant S14 was selected as the representative case because its overall RMSE was close to the cohort median and its optimized parameters did not fall on the search boundaries. The appendix presents the candidate parameter grid, top-ranked parameter combinations, selected optimal parameter pair, site-specific RMSE values, and measured-versus-simulated skin-temperature trajectories.

To examine whether the estimated water-film parameters were sensitive to the temporal resolution of the input data, an additional 10-s sensitivity analysis was performed. The main water-film calibration was conducted at the 1-min resolution to maintain consistency with the TPV and physiological analyses. Since 10-s six-directional radiation and skin-temperature measurements were available during the 10-min post-mist period, T_{mrt} was calculated at the 10-s resolution from six-directional radiation data. The same JOS-3 water-film calibration procedure was then repeated using 10-s environmental inputs and 10-s skin-temperature observations. To isolate the effect of temporal resolution, the initial-state alignment procedure, mist-affected body segments, fitted skin-temperature sites, water-film decay equation, parameter search grid, and optimization criterion were kept identical to those used in the 1-min main calibration. The only difference was that the post-mist simulation was updated at a 10-s rather than a 60-s time step.

2.7.3 Extrapolative simulation

Finally, the distributions of ω_0 and τ across the 20 participants were obtained and used for subsequent post-misting thermal-state simulations. To extrapolate local skin temperature responses during 1 h of tree-shaded walking after MsU exposure, the measured environmental conditions recorded during minutes 51 – 60 of the experiment were cyclically imposed 6 times as boundary inputs to the extended JOS-3 model (see Section 4.3.4).

3. Results

3.1. Thermal environment during the experiment

3.1.1 Outdoor microclimatic conditions

The field experiment was conducted in August 2025. Outdoor meteorological conditions during the experimental period were obtained from site-specific weather data provided by the meteorological station (Chen et al., 2025) (Fig. 5). The station is installed on the rooftop of the State Key Laboratory of Subtropical Building Science at South China University of Technology. As shown in Fig. 5, summertime outdoor conditions in this hot-humid region are characterized by high temperature and high humidity, with a mean monthly T_a of 28.2 °C, mean RH of 90.1%.

3.1.2 Thermal environment during the experiment

For the 20 samples, the thermal-environment data recorded at the questionnaire time points during the formal experiment are presented in Fig. 6 as box-and-line plots. The box shows the interquartile range (25th – 75th percentiles), with the horizontal line indicating the median. The whiskers denote the lowest and highest non-outlier values within $1.5 \times \text{IQR}$, and points beyond the whiskers are plotted as outliers. The symbols overlaid on the boxplots indicate the mean values, and the straight lines connecting these symbols illustrate the variation trend of the mean across time. Minutes 0 – 15 correspond to walking in tree shade, 16 – 25 to the first MsU exposure, 26 – 40 to walking in the sun, 41 – 50 to the second MsU exposure, and 51 – 60 to walking in tree shade. The MsU stages are highlighted by the gray-shaded background.

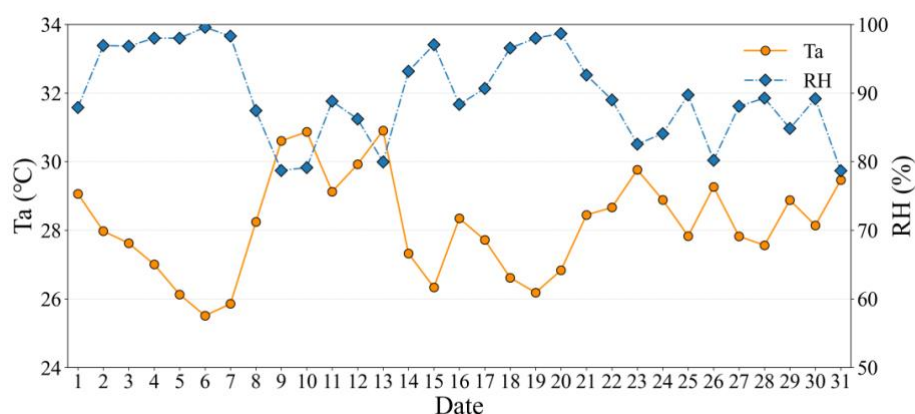
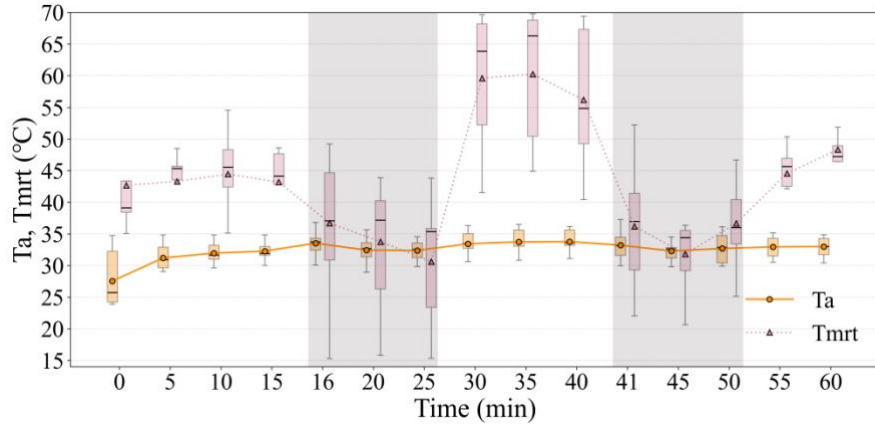
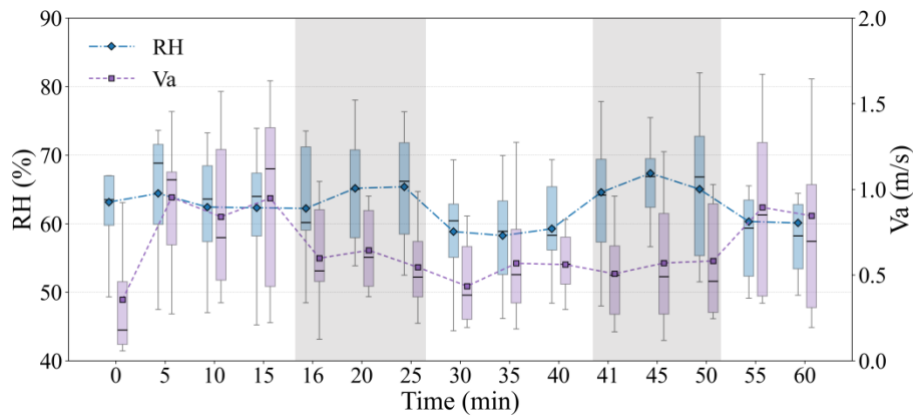


Fig.5. The monthly mean climate variations in Guangzhou city (August 2025).

As shown in Fig. 6a, the T_a exhibited limited fluctuation throughout the protocol, whereas the T_{mrt} varied substantially, with clearly higher values in the sun-exposed section than in the tree-shaded section. Independent-samples t-tests indicated that the T_a under the MsU (32.3 °C) did not differ significantly from that in the tree-shaded section ($p = 0.069$), but was significantly lower than that in the sun-exposed section (33.6 °C, $p < 0.001$), with an average reduction of 1.3 °C relative to sun exposure. For comparison, Kyogoku and Takebayashi reported a cooling capacity of approximately 0.5 – 1.0 °C for a misting system installed in an open park space (Kyogoku and Takebayashi, 2023). This comparison indicates that combining misting with shading may enhance the T_a reduction compared with misting alone, although the cooling magnitude remains dependent on site conditions, background weather, and system configuration.



a) Statistics of T_a and T_{mrt} .



b) Statistics of RH and V_a .

Fig.6. Thermal-environment conditions throughout the experiment.

The T_{mrt} under the MsU (35.2 °C) was significantly lower than that in both the shaded and sun-exposed segments ($p < 0.001$), being 24.0 °C lower than in the sun-exposed section (59.1 °C) and 9.9 °C lower than in the tree-shaded segment (45.1 °C). As shown in Fig. 6b, the RH under the MsU was significantly higher than in the sun-exposed section ($p < 0.001$) and the tree-shaded section ($p < 0.01$); its mean value (64.9%) was 6.2% higher than in the sun-exposed section and 3.3% higher than in the tree-shaded section (64.7%). V_a under the MsU was significantly lower than in the tree-shaded section ($p < 0.001$); the mean value (0.6 m/s) was 0.3 m/s lower than in the tree-shaded section (0.9 m/s), while the difference from the sun-exposed section was not significant ($p = 0.207$).

To further clarify the different contributions of the umbrella canopy, the operating MsU, and the tree shading to the radiant thermal environment, T_{mrt} was further compared under three conditions: under the MsU without mist operation, under the operating MsU, and in the tree-shaded section at the corresponding time points. The mean T_{mrt} under the MsU without mist operation was 40.9 °C, whereas the mean T_{mrt} under the operating MsU was 35.2 °C. The difference was significant according to the independent-samples t-test ($p < 0.001$). These two values represent the thermal-environment effects of physical shading alone and combined shading–misting, respectively, at the pedestrian scale. Also, the result of paired-samples t-test showed significant difference between

the T_{mrt} in the tree-shaded walking section and that under the MsU without mist operation at the same time points ($p < 0.001$). The mean T_{mrt} during tree-shaded walking was 45.1 °C, whereas the corresponding mean T_{mrt} under the MsU without mist operation was 40.9 °C. These results indicate that, compared with the naturally shaded section formed by *Michelia alba* planted at approximately 2.5 m intervals, the umbrella canopy provided a more stable overhead tree shading effect and further improved the pedestrian-level radiant thermal environment. When misting was activated, the thermal environment was further improved.

3.1.3 Integrated thermal indices

To evaluate the pedestrian-perceived thermal environment created by the MsU, UTCI and PET were compared across the three exposure conditions. Results of paired sample t-test indicated statistically significant differences in both UTCI and PET among the sun-exposed, tree-shaded, and MsU conditions ($p < 0.001$). In terms of mean values, the sun-exposed section yielded a UTCI of 40.8 °C and a PET of 47.0 °C; the tree-shaded section yielded a UTCI of 37.4 °C and a PET of 37.3 °C; and the MsU yielded a UTCI of 36.2 °C and a PET of 35.1 °C. These results indicate that, for summer walkways in hot-humid climates, the MsU can effectively improve the pedestrian-scale thermal environment. Relative to the sun-exposed section, the umbrella reduced UTCI by 4.6 °C and PET by 9.7 °C; relative to the tree-shaded section, it reduced UTCI by 1.2 °C and PET by 2.2 °C.

Overall, these findings show that the sequential distribution of sun exposure, tree shade, and mist-shading nodes along the walking route constituted a clearly ordered thermal-exposure process, providing the basis for subsequent analyses of non-steady-state physiological and psychological responses.

3.2. Abrupt changes upon entering the MsU

To characterize participants' thermal exposure when entering the MsU from different preceding walking environments, this section focuses on abrupt changes in environmental parameters and local skin temperatures within 1 min after entering the MsU.

3.2.1 Thermal environment

To examine the pedestrian-level abrupt change in the thermal environment immediately after entering the MsU, the thermal-environment parameters recorded within 1 min before and after entry into the MsU were compared.

In the time domain, paired-samples t-tests were performed on the 1.7 m-height measurements comparing conditions immediately before and 1 min after entering the umbrella. The results showed that, when participants moved from the tree-shaded section into the MsU, T_a , V_a , T_{mrt} , and UTCI changed significantly ($p < 0.001$, $p = 0.004$, $p = 0.001$, and $p = 0.029$, respectively). Specifically, T_a increased by 0.2 °C, V_a decreased by 0.3 m/s, mean T_{mrt} decreased by 5.5 °C, and UTCI decreased by 1.2 °C; When participants moved from the sun-exposed section into the MsU, T_{mrt} , UTCI, and

PET decreased significantly. T_{mrt} decreased by 21.3 °C, UTCI by 4.2 °C, and PET by 8.7 °C.

In the spatial domain, paired-samples t-tests were applied to T_a and RH measured at 1.1 m and 1.7 m inside the MsU. T_a at 1.7 m (32.8 °C) was significantly lower than that at 1.1 m (33.5 °C) ($p < 0.01$), and RH at 1.7 m (64.9%) was significantly higher than that at 1.1 m (62.1%) ($p < 0.01$). These results indicate a vertical gradient within the microenvironment created by the MsU, with the air around participants' head level being cooler and more humid than around the lower body.

3.2.2 Physiological responses

To compare the physiological responses of participants to such abrupt thermal-environment changes, paired t-tests were performed on skin temperatures at the eight local sites measured immediately before and 1 min after entering the MsU.

The results showed that, after walking from the tree-shaded section into the MsU, significant changes were observed at the forehead, back, arm, and hand ($p = 0.027$, 0.031, 0.009, and 0.050, respectively), with reductions of 0.3 °C, 0.2 °C, 0.3 °C, and 0.3 °C at these sites.

After walking from the sun-exposed section into the MsU, significant changes were found at the chest, back, shoulder, and hand ($p = 0.013$, 0.007, 0.035, and 0.037, respectively), with decreases of 0.4 °C, 0.9 °C, 0.5 °C, and 0.5 °C, respectively. The mean value of minute-to-minute change in skin-temperature at 8 points (Fig. 7) further show pronounced changes in upper-body local skin temperatures during the two entries into the MsU.

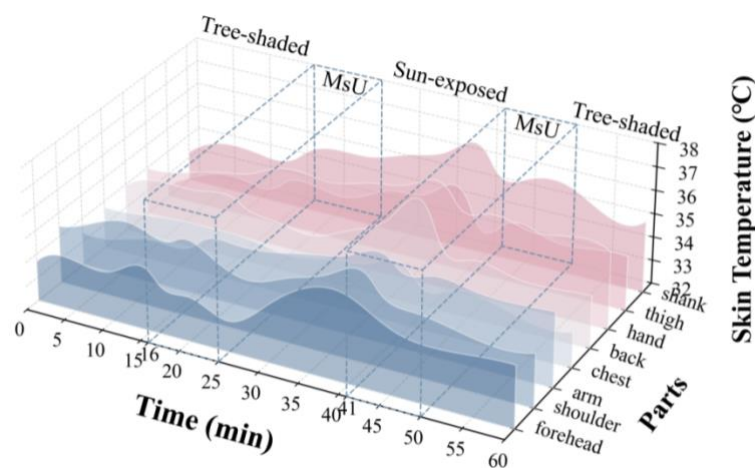


Fig.7. Mean local skin temperatures at eight sites.

3.3. Temporal dynamics of TP

3.3.1 Overall trend

The statistical results of TPV over the entire experiment is shown in Fig. 8. The box shows the interquartile range (25th–75th percentiles), with the horizontal line indicating the median. The whiskers denote the lowest and highest non-outlier values within $1.5 \times \text{IQR}$, and points beyond the whiskers are plotted as outliers. The overlaid circles

represent mean values, and the straight lines connecting the mean values indicate the temporal variation in the mean. The MsU stages are highlighted by the gray-shaded background.

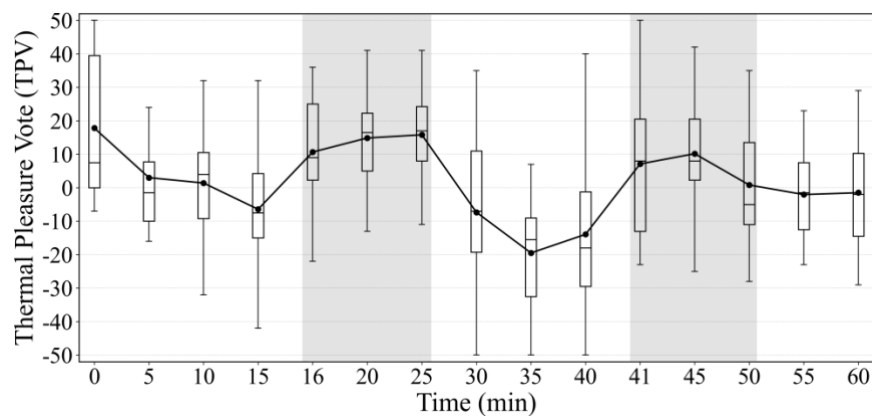


Fig.8. Boxplots of TPV during the whole experiment.

To provide an overall view of thermal-emotional states under different thermal exposures, TPV data were grouped by exposure condition. The results of independent-samples t-tests showed that TPV differed significantly among the sun-exposed, tree-shaded, and MsU conditions ($p < 0.001$). In terms of mean values, TPV under the MsU (9.9) was higher than that under tree shade (-1.0) and sun exposure (-13.6), indicating an increase of 10.9 and 23.5 vote units, respectively. Overall, the MsU markedly elicited TP during walking. Although the mean votes in all three conditions still fell within the “unpleasant” range, walking under sun exposure was substantially more unpleasant than walking under tree shade. These results indicate that thermal pleasure is not a steady-state sensation; rather, it varies dynamically with changing thermal exposures during continuous walking.

For consistency and comparability with existing and future studies on cooling interventions along outdoor walkways, the TSV of the 20 participants throughout the experiment were summarized in Fig. 9 using the same format as Fig. 8. Results independent-samples t-tests showed significant differences in TSV among the three environmental conditions ($P < 0.001$). Under the MsU condition, the mean TSV was 7.3, which was closer to “Neutral” and corresponded to approximately 0.4 on the 7-point voting scale. During walking under tree shade, the mean TSV was 15.1, corresponding to approximately 0.9 on the 7-point scale and approaching “Slightly warm”. During walking under direct solar exposure, the mean TSV increased to 27.6, corresponding to approximately 1.9 on the 7-point scale and approaching “Warm”. These results indicate that the MsU significantly reduced the thermal sensation of pedestrians and shifted their perceived thermal state toward neutrality.

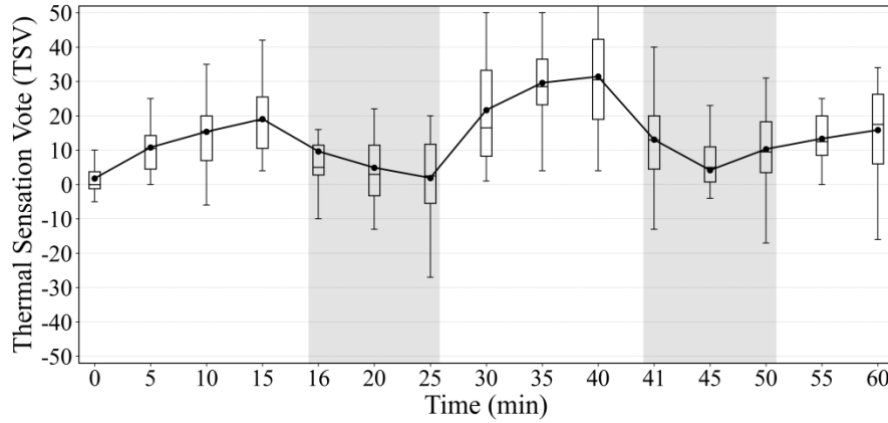


Fig.9. Boxplots of TSV during the whole experiment.

3.3.2 Relationship with thermal history

To examine whether the pre-entry walking environment (i.e., prior thermal history) affected the induction of thermal pleasure upon entering the MsU, Δ TPV was calculated for each entry into the MsU. Specifically, Δ TPV was defined as the difference between the TPV recorded at the end of the 15-min walking stage (sun-exposed or tree-shaded) and the TPV recorded at the 1st minute after entering the MsU. Both the data distributions and the minimum, maximum, quartiles, mean, and median of each group for Δ TPV, as well as the paired-samples t-test results, are presented in Fig. 10, where ns indicates no significant difference ($P > 0.05$). The result showed no significant difference between entries from sun exposure and from tree shade ($p=0.519$). This indicates that entering the MsU increased TP to a comparable extent regardless of the preceding walking environment.

To assess the influence of post-cooling thermal history (i.e., the walking environment after leaving the MsU) on thermal pleasure dissipation, TPV_decay was compared between the two post-misting walking stages (tree shade vs. sun exposure) using paired-samples t-tests. Both the data distributions and the minimum, maximum, quartiles, mean, and median of each group for TPV_decay, as well as the paired-samples t-test results, are also presented in Fig. 10, where ** indicates a highly significant difference between the two groups ($P < 0.01$).

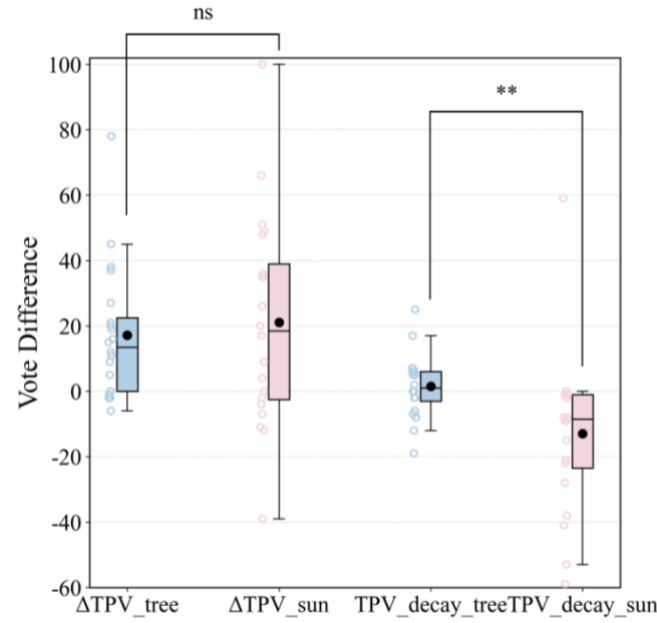


Fig.10. TPV throughout the experiment.

The result showed that TPV_decay was significantly larger (i.e., a greater loss of TP) during walking in the sun-exposed section than in the tree-shaded section ($p = 0.011$), with a mean difference of approximately 11.0 vote units. This indicates that post-misting thermal history strongly modulated the dissipation of TP. However, classification by exposure type alone cannot explain the physiological basis underlying these differences in thermal-pleasure dissipation across thermal histories.

3.4. Relationships between skin temperature and TP

3.4.1 State-dependent correlations

As shown in Section 3.2, upper-body local skin temperatures responded rapidly to the thermal exposure induced by the misting environment. Section 3.3 further demonstrated that TP is influenced by short-term thermal history. This raises the question of whether local skin temperature can serve as a physiological bridge linking a dynamic thermal environment to TP. This section tests the explanatory relevance of local skin temperature for TP.

To examine the relationship between the static values of local skin temperature and TP, correlation tests were performed between eight-point skin temperature and TPV (Fig. 11a). As visualized in Fig. 10a, the pairwise Pearson correlation structure is presented in the upper triangular matrix, where color denotes the sign and magnitude of r . The “Summary” panel further highlights the correlations between each physiological variable and the target subjective response, with line color indicating statistical significance and line thickness indicating the absolute strength of the correlation.

The results of correlation tests showed that TPV was not significantly associated with skin temperature at the calf ($p = 0.147$), thigh ($p = 0.095$), or upper arm ($p=0.381$). In contrast, TPV was highly significantly correlated with temperatures at the forehead, shoulder, back, hand, and chest ($p < 0.001$), and the shoulder temperature was also

significantly associated with TPV ($p = 0.025$). In terms of correlation strength (r), TPV showed strong associations with temperatures at the head ($r = -0.22$) and back ($r = -0.20$). These results indicate that upper-body local skin temperature can effectively reflect the instantaneous state of TP, which was caused by MsU.

3.4.2 Cumulative effects of thermal history on TP dissipation

To quantify cumulative thermal exposure across different thermal histories, the area under the curve (AUC) of eight-point skin temperatures was calculated. To examine the relationship between cumulative thermal exposure and thermal-pleasure dissipation, correlations tests were conducted between AUC values at each site and TPV_decay (Fig.11b).

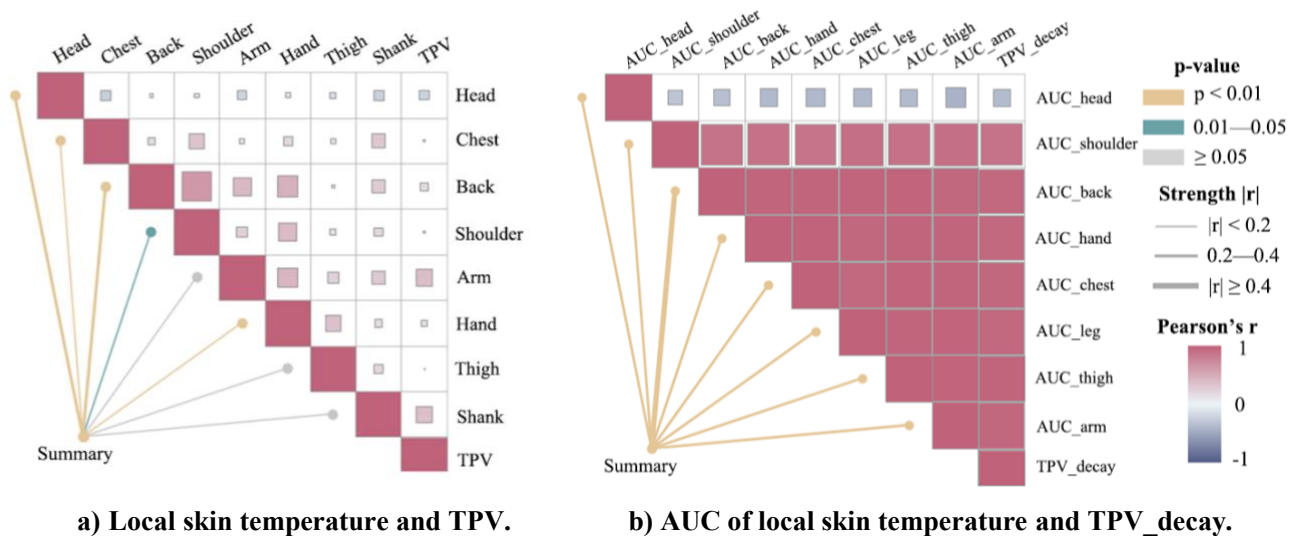


Fig.11. The results of Correlation test.

The results of correlation tests showed significant associations between TPV_decay and AUC-derived metrics of local skin temperature ($p = 0.003, 0.002, 0.001, 0.001, 0.002$), with an especially strong correlation for the AUC_back ($r = -0.42$). This pattern is consistent with the measured vertical distribution of the MsU microenvironment described in Section 3.2.1, which showed stronger cooling and humidification near the upper-body level than near the lower-body level.

Overall, these findings suggest that thermal-pleasure dissipation is not determined solely by instantaneous thermal state, but is progressively governed by thermal load accumulated through thermal history.

4. Discussion

4.1. From instantaneous pleasure to persistence-oriented cooling

design

The results in Section 3.3.2 indicate that pedestrians can obtain a marked increase in TP within a short time after entering the MsU, regardless of whether they approach it from direct sun exposure or from shade. This pattern is consistent with the “corrective

pleasure” mechanism described by alliesthesia theory (Ali Smail et al., 2024; Parkinson and De Dear, 2015), whereby a pronounced positive affective response is triggered when an external stimulus rapidly alleviates an individual's current thermal-load deviation. Prior studies similarly report that misting systems and localized cooling facilities can effectively improve pedestrians' perceived thermal environment and subjective comfort within a short period (Black-Ingersoll et al., 2022; Kusaka et al., 2022; Zhang et al., 2021).

This study further shows that, during the walking period after leaving the cooling point, the decay of TP is not necessarily symmetric or consistent; instead, it is strongly modulated by the post-cooling environmental conditions. This asymmetry likely reflects pedestrians' combined thermophysiological and psychological adaptation during subsequent walking. Physically, misting can sustain elevated evaporative heat loss during the drying phase, whereas psychologically, continued tree shade may reinforce adaptive processes (Nikolopoulou and Steemers, 2003) and thus moderate the decay of TP. Taken together, these findings highlight a key shift in evaluating localized cooling strategies along landscape walkways. Rather than focusing solely on whether TP can be elicited within a cooling node, the experience-critical question becomes how long this pleasant state can be sustained after departure. In this sense, misting acts more like a “trigger” of TP, while the subsequent walking condition—particularly the presence of continuous shading—regulates the persistence and depletion rate of TP.

This asymmetry can be explained by the physiological mechanism of heat-load re-accumulation. The intense evaporative cooling induced by misting is sufficient to provide recovery and induces TP. Once pedestrians re-enter the walking environment, however, the trajectory of TP becomes governed by the rate at which local thermal load re-accumulates. Shaded environments reduce shortwave radiative input and suppress re-warming of upper-body surfaces, thereby substantially slowing skin-temperature rebound and, in turn, delaying the decay of TP. In contrast, under direct solar exposure, rapid local heat-load accumulation can exhaust the pleasant sensation within a much shorter time (Ulpiani and Zinzi, 2023). Overall, our results suggest that the dynamic evolution of mist-induced TP during walking is not determined by the instantaneous cooling intensity alone, but is progressively dominated by upper-body skin-temperature states shaped by thermal history.

4.2. Translating thermal pleasure dissipation into a physiological

threshold

A key step in addressing the spacing of cooling points is to translate the abstract notion of “pleasure persistence” into a measurable and predictable physical quantity. Section 3.4.1 has demonstrated that instantaneous TPV is significantly associated with concurrent upper-body skin temperatures. This state-level coupling indicates that local skin temperature can serve as an effective physiological indicator of momentary TP. Building on this relationship, weighted linear regression can be used to define a critical skin temperature corresponding to $TPV = 0$, i.e., the boundary at which TP is exhausted and transitions into unpleasantness. Weighted linear regression between the mean TPV

within each 0.5 °C temperature bin and the corresponding local skin temperature was performed, with results shown in Fig. 12 and Eqs. (7)–(12).

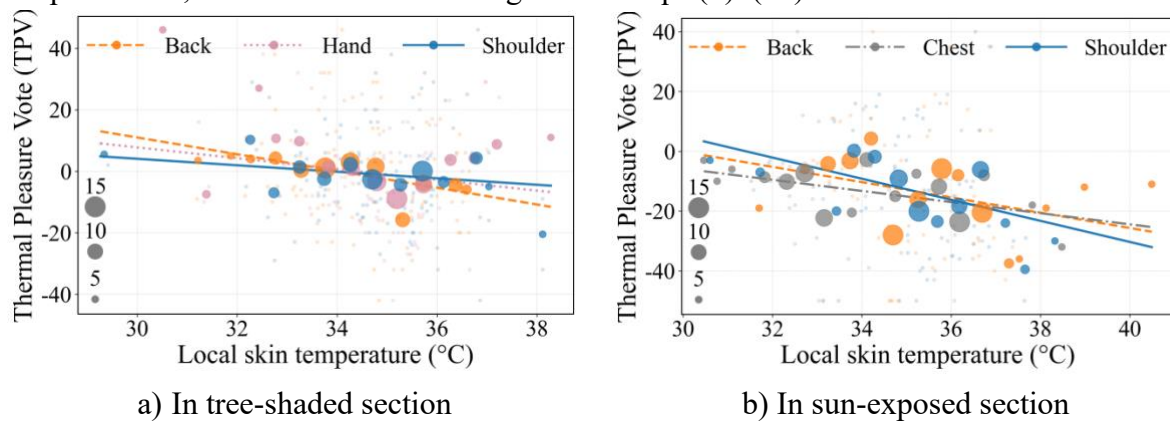


Fig.12 Relationships between local skin temperature and TPV.

$$TPV_{tree} = -0.608T_{shoulder,t} + 129.885 \quad (P = 0.000, R^2 = 0.37) \quad (7)$$

$$TPV_{tree} = -7.537T_{back,t} + 262.633 \quad (P = 0.000, R^2 = 0.68) \quad (8)$$

$$TPV_{tree} = -10.35T_{hand,t} + 360.354 \quad (P = 0.000, R^2 = 0.83) \quad (9)$$

$$TPV_{sun} = -3.372T_{shoulder,t} + 105.388 \quad (P = 0.000, R^2 = 0.25) \quad (10)$$

$$TPV_{sun} = -2.556T_{back,t} + 129.885 \quad (P = 0.000, R^2 = 0.37) \quad (11)$$

$$TPV_{sun} = -1.863T_{chest,t} + 50.099 \quad (P = 0.000, R^2 = 0.21) \quad (12)$$

In the tree-shaded condition, the regression results for the head and chest were not significant ($p = 0.109$ and $p = 0.085$), whereas in the sun-exposed condition, the head and hand were not significant ($p = 0.626$ and $p = 0.077$). After calculation, under tree shade, the threshold temperatures corresponding to $TPV = 0$ were approximately 36.0 °C (shoulder), 34.9 °C (back), and 34.8 °C (hand). Under direct solar exposure, the corresponding thresholds were approximately 31.3 °C (shoulder), 30.0 °C (back), and 26.9 °C (chest).

Notably, for the sun-exposed samples, 98% of the measured shoulder skin temperatures and 100% of the back and chest temperatures exceeded these thresholds. This indicates that, from the perspective of sustaining TP, prolonged unshaded segments are not advisable. For tree-lined landscape walkways, this conceptual bridge allows the spacing problem to be reframed as a time-to-threshold problem: under given environmental conditions, how long does it take—after leaving the MsU—for the key upper-body skin temperatures to reach the critical level? Addressing this issue would provide guidance for planning the spacing of MsUs along landscaped pedestrian walkways.

4.3. Extending JOS3 model to capture spray-induced evaporative

cooling

Section 4.2 reframed the spacing of MsUs as a time-to-threshold problem: after leaving the MsU, how long can key upper-body skin temperatures remain below the $TPV = 0$ threshold under subsequent walking conditions? Answering this question requires a model that can reproduce the post-misting rebound of local skin temperature. Li et al. proposed a JOS-3-based framework for understanding thermal alliesthesia along urban walking routes, in which skin wettedness was incorporated into the evaporative heat-loss pathway and linked to body thermal storage (Li et al., 2026). This provides an important methodological reference for using thermophysiological modelling to interpret dynamic thermal alliesthesia during walking. However, the wetness process in the present mist-shading experiment differs from the standard sweat-related skin wettedness represented in JOS-3. In addition to endogenous sweat evaporation, mist exposure may deposit external water on the skin and clothing surface, forming a residual water film that continues to evaporate after participants leave the MsU. Therefore, this study retained the original JOS-3 sweat-related evaporation pathway and further extended the model by adding an exogenous mist-induced water-film evaporation term.

To determine how long the local skin temperatures associated with TP remain below their critical thresholds after MsU exposure, the extended JOS-3 model was used to simulate post-misting skin-temperature dynamics during prolonged tree-shaded walking. By incorporating the cooling effect of residual water-film evaporation, the model was able to represent the delayed skin-temperature rebound that would not be captured by the original JOS-3 framework.

At the end of misting, the simulated mean skin temperature field was aligned with the measured thermal state beneath the MsU. After preconditioning, the mean skin temperatures at the eight monitored sites were 34.5 °C at the forehead, 33.9 °C at the chest, 34.2 °C at the back, 34.4 °C at the shoulder, 35.2 °C at the arm, 35.3 °C at the hand, 34.3 °C at the thigh, and 35.8 °C at the calf.

Using the measured environmental and skin-temperature data from minutes 51 – 60, the initial effective wettedness ω_0 and drying time constant τ were estimated for each participant. Across the 20 samples, the mean ω_0 was 0.7 (SD 0.27), and the mean τ was 13.7 min (SD 3.70). This suggests that the evaporative cooling effect induced by misting generally persisted for approximately 14 min after exposure ceased, although substantial inter-individual variation was evident.

The optimized parameter sets provided satisfactory agreement between simulated and measured post-misting skin temperatures (Fig. 13). RMSE values were approximately 1.2 °C across the three evaluated regions, with the smallest error observed for the back. The largest discrepancy was observed for the hand. This is consistent with the fact that the hand is a distal and exposed body part with high behavioural variability during outdoor walking and mist exposure. In the present experiment, participants' hand

posture and movement were not constrained, and some participants raised their hands or touched the mist under the MsU. Such behaviour-induced local wetting and cooling could not be fully represented by the uniform segment-level environmental inputs and simplified water-film parameterization used in the JOS-3 simulation. Previous studies have shown that hand, wrist, or forearm skin temperatures can be informative for evaluating overall thermal sensation or thermal comfort, but local skin temperatures are also sensitive to individual physiological differences, local exposure conditions, and adaptive behaviours (Chaudhuri et al., 2018; Wang et al., 2024; Yeom and Delogu, 2021). Therefore, the discrepancy in hand temperature should be interpreted as a limitation of simulating a highly variable local cooling response, rather than as evidence that hand temperature is irrelevant to TP. For the subsequent extrapolation, back skin temperature was selected because it was also an upper-body site affected by the MsU, but its exposure condition was more stable and its simulated trajectory agreed more closely with the measured data. It also showed a strong association with TPV decay, making it a more robust physiological variable for estimating the persistence of post-misting TP.

The 10-s sensitivity analysis produced parameter estimates comparable to those from the 1-min main calibration. The estimated mean ω_0 was 0.7 (SD 0.26) and the τ was 13.4 min (SD 4.52) for the 10-s calibration. Paired comparisons showed no significant systematic differences ($p > 0.05$) in either parameter. The overall RMSE decreased from 1.328 ± 0.789 °C in the 1-min calibration to 1.160 ± 0.640 °C in the 10-s calibration, indicating slightly improved fitting of short-term skin-temperature dynamics. These results suggest that the estimated water-film parameters were not materially affected by increasing the temporal resolution of environmental and skin-temperature inputs from 1 min to 10 s. Therefore, the 1-min calibration was retained as the main analysis for consistency with the overall TPV and physiological datasets.

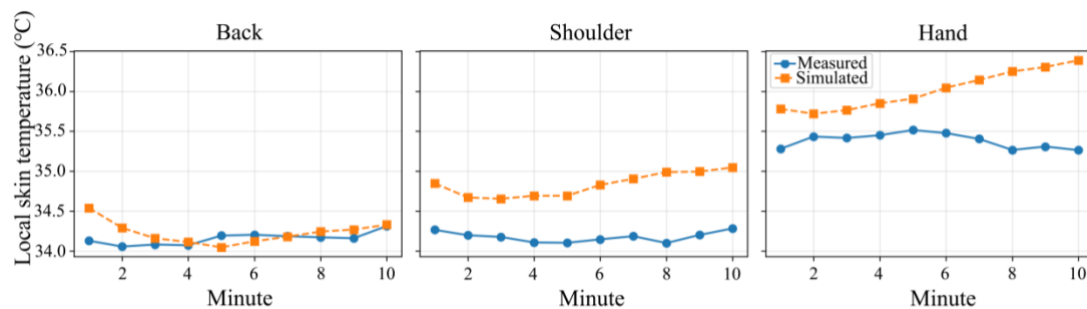


Fig.13. Comparison between simulated and experimentally measured values of skin-temperatures.

The validated parameter sets were then used to extrapolate skin-temperature responses during 1 h of tree-shaded walking after MsU exposure. Under the mean boundary conditions of the post-umbrella tree-shaded environment ($T_a = 33.0$ °C, $T_{mrt} = 46.4$ °C, $RH = 60.2\%$, and $V_a = 0.83$ m/s; $UTCI = 38.5$ °C), the simulated back-skin temperature trajectories for all 20 participants showed a gradual warming trend (Fig. 14). The simulation results indicate that back skin temperature reached the critical threshold corresponding to $TPV = 0$ (34.9 °C) at approximately 28 min after leaving the misting point.

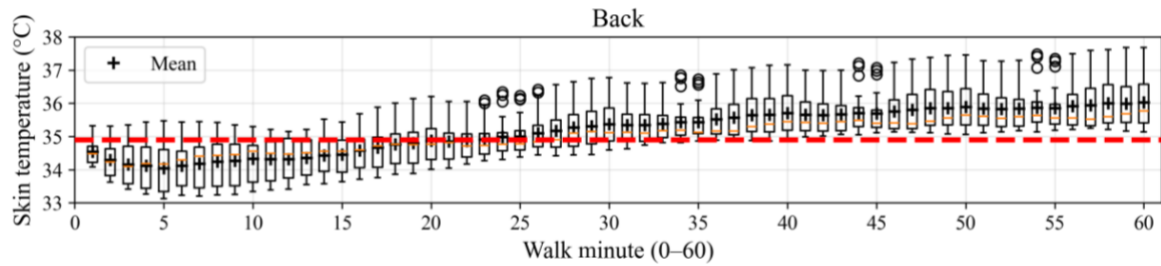


Fig.14. Simulated back-skin temperature during 60 min walking in the post-umbrella tree-shaded environment.

Assuming a walking speed of 3.0 km/h, this time-to-threshold corresponds to an indicative spacing of about 1.4 km. From a planning perspective, this provides a first-order estimate of the maximum effective spacing between adjacent MsUs along tree-shaded pedestrian walkways under the tested shaded-continuation condition. Importantly, this spacing is scenario-dependent rather than universal: the proposed time-to-threshold framework can be recalculated for other combinations of T_{mrt} , RH, V_a , walking speed, and misting intensity.

4.4. Limitations and future work

Due to constraints in the experimental schedule, the observed T_a range was limited to 26.0–37.1 °C, and the findings are therefore most applicable to summer conditions in hot-humid climates. Therefore, the design spacing proposed in this study was derived under the specific climatic conditions and experimental protocol adopted here. Different climatic regions, activity states, exposure durations, and exposure intensities may lead to different appropriate spacing recommendations. Future studies should consider extending the investigation to a wider range of climate types, activity patterns, exposure durations, and exposure intensities.

To ensure sufficient induction of TP and to capture its evolution during exposure to misting, participants in this experiment were instructed to stand for 10 min under the misting condition after each entry, while being free to choose their position beneath the MsU. This fixed dwell time may not reflect all users' preferences in real-world settings. In future validation trials, we plan to better accommodate pedestrians' behavioral preferences by allowing them to control device activation, and to freely choose their posture and standing location during cooling exposure.

In addition, the direct outcomes of the simulations in this study have inherent limitations. The JOS-3 model is capable of representing thermophysiological responses at multiple body segments, and ideally requires spatially resolved environmental inputs, such as segment-specific T_{mrt} , V_a and T_a , because different body surfaces may be exposed to different radiative, convective, and evaporative conditions. However, in the present field experiment, environmental inputs were measured at representative pedestrian-scale points and were applied uniformly to the simulated body segments or target fitted sites. This simplification may introduce uncertainty in local skin-temperature prediction, particularly under the MsU, where mist exposure, air movement, and radiant shielding were spatially non-uniform. The extrapolation simulations used mean measured thermal-environment parameters under tree shade as

boundary conditions, whereas in real-world use the post-cooling walking environment along the walkway is not necessarily stable, and shading itself may be intermittent. Therefore, the simulated time-to-threshold and the derived spacing should be interpreted as scenario-specific estimates rather than exact predictions for all walkway configurations.

Moreover, the present simulations were based on healthy adults, and the results may not be generalizable to all age groups. Future work should extend the investigation to vulnerable populations (e.g., older adults), given their substantial representation among landscape-trail users (Tomasi et al., 2024). Importantly, the 1.4 km value should not be interpreted as a universal spacing standard; rather, it demonstrates a transferable method that converts dynamic thermal comfort into design-oriented spacing decisions. Variations in shading, wind speed, humidity, walking speed, and misting intensity will inevitably lead to different spacing outcomes, which can be evaluated within the same framework.

Another important limitation is that this study focused on TP as a subjective response related to enhancing the attractiveness of outdoor landscape walkways. However, TP is an immediate affective response and should not be directly equated with thermal comfort. Therefore, the findings related to TP in this study may not necessarily apply to analyses based on thermal comfort or thermal sensation. The similarities and differences among TP, thermal comfort, and thermal sensation in terms of their physiological and psychological feedback mechanisms deserve further investigation in future research.

Finally, the practical implementation of mist-based cooling facilities involves operational constraints that were not directly assessed in this study. Real-world MsU deployment requires a clean and continuous water supply, appropriate drainage, reliable pumping systems, and regular maintenance of nozzles, filters, pipes, and pumps. Nozzle blockage, scaling, uneven mist distribution under variable wind conditions, water and energy consumption, and hygiene management may all affect long-term performance (D'Orazio et al., 2023). In public urban spaces, water quality monitoring and regular cleaning or disinfection are also necessary to reduce potential microbial risks. Future studies should therefore evaluate not only the thermal and perceptual benefits of MsU systems, but also their water-use efficiency, energy demand, maintenance requirements, hygiene management, and adaptive operation strategies.

5. Conclusion

This study designed and installed a mist–shade umbrella at a lakeside campus walkway in a Cfa climate region in China. A field experiment was conducted to measure environmental parameters, local skin temperatures, and subjective responses as pedestrians entered and left the mist–shade umbrella from sun-exposed and tree-shaded sections, with the goal of determining an appropriate spacing strategy for this localized cooling device along outdoor trails. The main findings are as follows:

(1) The mist–shade umbrella significantly improved the pedestrian-scale thermal environment, mainly by reducing mean radiant temperature and enhancing evaporative cooling conditions. Compared with the sun-exposed and tree-shaded sections, mean radiant temperature under the umbrella decreased by approximately 25.0 °C and 10.9 °C, respectively, and UTCI decreased by 4.6 °C and 1.2 °C, indicating a stable instantaneous cooling effect for walking trails in Cfa climates.

(2) Misting rapidly elicited thermal pleasure, and the induction magnitude was not affected by the pre-cooling walking condition (sun vs. shade). In contrast, the post-cooling dissipation rate of thermal pleasure was highly sensitive to subsequent thermal history, decaying significantly faster in the sun-exposed section than in the tree-shaded section (35% vs. 3% within 10 min).

(3) Upper-body local skin temperature was a key physiological indicator of dynamic thermal pleasure. Instantaneous thermal pleasure was significantly associated with temperatures at the forehead, shoulder, back, chest, and back of the hand, whereas cumulative thermal-pleasure dissipation was significantly related to cumulative thermal load across body sites. Distinct skin-temperature thresholds for the loss of thermal pleasure were identified across environments (e.g., under tree-shade: shoulder $\approx$ 36.0 °C, back $\approx$ 34.9 °C; under sun: shoulder $\approx$ 31.3 °C, back $\approx$ 30.0 °C), beyond which thermal pleasure disappeared.

(4) By incorporating a mist-induced surface water-film evaporation mechanism into the JOS-3 thermophysiological model and validating it with field measurements, the extended model reasonably reproduced the post-misting evolution of upper-body skin temperature. Extrapolation simulations suggest that, under tree-shaded continuation conditions (UTCI = 38.5 °C) and a walking speed of 3.0 km/h, back skin temperature reaches the unpleasantness threshold at approximately 28 min after leaving the cooling point, corresponding to a walking distance of about 1.4 km. Accordingly, the recommended spacing of mist–shade umbrellas along landscape walkways in Cfa climates is approximately 1.4 km.

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References

- Ali Smail, S., Zemmouri, N., Djenane, M., Nikolopoulou, M., 2024. Investigating the transient conditions of “Sabat” space and its influence on pedestrian sensations during thermal walks. Algiers’ Casbah case study. *Building and Environment* 261, 111760. <https://doi.org/10.1016/j.buildenv.2024.111760>

- Belyamani, M.A., Hurley, R.F., Djamasbi, S., Somasse, G.B., Strauss, S., Zhang, H., Smith, M.J., Van Dessel, S., Liu, S., 2024. Local wearable cooling may improve thermal comfort, emotion, and cognition. *Building and Environment* 254, 111367.
- Black-Ingersoll, F., de Lange, J., Heidari, L., Negassa, A., Botana, P., Fabian, M.P., Scammell, M.K., 2022. A Literature Review of Cooling Center, Misting Station, Cool Pavement, and Cool Roof Intervention Evaluations. *Atmosphere* 13, 1103. <https://doi.org/10.3390/atmos13071103>
- Bröde, P., Fiala, D., Błażejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., Tinz, B., Havenith, G., 2012. Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *Int J Biometeorol* 56, 481–494. <https://doi.org/10.1007/s00484-011-0454-1>
- Cabanac, M., 1979. Sensory Pleasure. *The Quarterly Review of Biology* 54, 1–29. <https://doi.org/10.1086/410981>
- Chai, T., Draxler, R.R., 2014. Root mean square error (RMSE) or mean absolute error (MAE)? – Arguments against avoiding RMSE in the literature. *Geoscientific Model Development* 7, 1247–1250. <https://doi.org/10.5194/gmd-7-1247-2014>
- Chaudhuri, T., Zhai, D., Soh, Y.C., Li, H., Xie, L., 2018. Thermal comfort prediction using normalized skin temperature in a uniform built environment. *Energy and Buildings* 159, 426–440. <https://doi.org/10.1016/j.enbuild.2017.10.098>
- Chen, S., Zhao, L., Li, Q., Yang, J., Zhang, S., Nie, Z., Wagner, A., 2025. Linking Outdoor Heatwave and Indoor Overheating: A Multi-Timescale Coupling Framework for Residential Buildings in Hot and Humid Climates. *Building and Environment* 114086.
- Cohen, J., 2013. *Statistical power analysis for the behavioral sciences*. routledge.
- de Dear, R., 2011. Revisiting an old hypothesis of human thermal perception: alliesthesia. *Building Research & Information* 39, 108–117. <https://doi.org/10.1080/09613218.2011.552269>
- De Masi, R.F., Ruggiero, S., Villano, F., Kytrilaki, A., Efthymiou, C., Papadaki, D., Assimakopoulos, M.N., 2026. Performance and seasonal trade-offs of passive daytime radiative cooling roofs in European buildings. *Energy and Buildings* 350, 116621. <https://doi.org/10.1016/j.enbuild.2025.116621>
- Di Giuseppe, E., Ulpiani, G., Cancellieri, C., Di Perna, C., D’Orazio, M., Zinzi, M., 2021. Numerical modelling and experimental validation of the microclimatic impacts of water mist cooling in urban areas. *Energy and Buildings* 231, 110638. <https://doi.org/10.1016/j.enbuild.2020.110638>
- D’Orazio, M., Di Perna, C., Di Giuseppe, E., Coccia, G., Summa, S., 2023. Evaluation of effectiveness and resources consumption of water mist spray systems in Mediterranean areas by predictions based on LSTM Recurrent Neural Networks. *Sustainable Cities and Society* 99, 104894. <https://doi.org/10.1016/j.scs.2023.104894>
- Dzyuban, Y., Hondula, D.M., Vanos, J.K., Middel, A., Coseo, P.J., Kuras, E.R., Redman, C.L., 2022. Evidence of alliesthesia during a neighborhood thermal walk in a hot and dry city. *Science of the Total Environment* 834, 155294.

- Faul, F., Erdfelder, E., Lang, A.-G., Buchner, A., 2007. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods* 39, 175–191. <https://doi.org/10.3758/BF03193146>
- Gallacher, C., Boehnke, D., 2025. Pedestrian thermal comfort mapping for evidence-based urban planning; an interdisciplinary and user-friendly mobile approach for the case study of Dresden, Germany. *Int J Biometeorol* 69, 2895–2912. <https://doi.org/10.1007/s00484-024-02830-2>
- Girden, E.R., 1992. ANOVA: Repeated measures. sage.
- Höppe, P., 1999. The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. *Int J Biometeorol* 43, 71–75. <https://doi.org/10.1007/s004840050118>
- Hu, H., Zhou, H., Cheng, J., Shu, T., 2025. The effects of green apartment living, neighborhood greenspace exposures and greenspace exposures in activity space on residents' walking behaviors and mental health in China. *Applied Geography* 177, 103545. <https://doi.org/10.1016/j.apgeog.2025.103545>
- Huang, C., Cai, J., Lin, Z., Zhang, Q., Cui, Y., 2017. Solving model of temperature and humidity profiles in spray cooling zone. *Building and Environment* 123, 189–199.
- Hvid, L.G., Steenberg, J.L., Roy, F., Skovgaard, L., 2025. Outdoor walking exercise therapy improves walking capacity and well-being in persons with multiple sclerosis: A randomized controlled trial. *Annals of Physical and Rehabilitation Medicine* 68, 101985.
- ISO 7726:1998(E), 1998. Ergonomics of the thermal environment--Instruments for measuring physical quantities. Switzerland: International Organization for Standardization.
- ISO 8996, 2005. Ergonomics of the Thermal Environment - Determination of Metabolic Rate.
- ISO 9886 (E), 2004. Evaluation of thermal strain by physiological measurements. Switzerland.
- Jendritzky, G., de Dear, R., Havenith, G., 2012. UTCI—Why another thermal index? *Int J Biometeorol* 56, 421–428. <https://doi.org/10.1007/s00484-011-0513-7>
- Kusaka, H., Nakamura, Y., Asano, Y., 2022. UV Parasol, Dry-Mist Spraying, and Street Trees as Tools for Heat Stress Mitigation. *Journal of the Meteorological Society of Japan. Ser. II* 100, 677–685. <https://doi.org/10.2151/jmsj.2022-035>
- Kyogoku, S., Takebayashi, H., 2023. Experimental verification of mist cooling effect in front of air-conditioning condenser unit, open space, and bus stop. *Atmosphere* 14, 177.
- Li, S., Lai, L., Wang, C., Yao, C., Wang, Jiashuo, Wang, Junsong, Mao, H., Santamouris, M., 2026. Evaporative cooling mist-spray system to enhance thermal comfort in urban outdoor premises. *Energy and Buildings* 352, 116834. <https://doi.org/10.1016/j.enbuild.2025.116834>
- Li, Y., Zhong, X., Xie, Y., de Dear, R., Lu, S., Lin, B., Niu, J., 2026. Thermal comfort on the move: Understanding thermal alliesthesia on urban walking routes.

- Building and Environment 295, 114434.
<https://doi.org/10.1016/j.buildenv.2026.114434>
- Li, Z., Yang, B., Jin, D., Li, X., Wang, F., Li, A., 2022. The synergy effect of temporal and spatial alliesthesia on occupants' thermal comfort in air-conditioned temporarily occupied spaces (TOS). *Building and Environment* 210, 108699.
- Li, Z., Zhou, L., Hong, X., Qiu, S., 2024. Outdoor thermal comfort and activities in urban parks: An experiment study in humid subtropical climates. *Building and Environment* 253, 111361.
- Lin, Z., Guldmann, J.-M., Liu, Z., Zhao, L., 2018. Influence of Trees on the Outdoor Thermal Environment in Subtropical Areas: An Experimental Study in Guang Zhou, China. *Sustainable Cities and Society* 42.
<https://doi.org/10.1016/j.scs.2018.07.025>
- Liu, S., Nazarian, N., Hart, M.A., Niu, J., Xie, Y., de Dear, R., 2021. Dynamic thermal pleasure in outdoor environments - temporal *alliesthesia*. *Science of The Total Environment* 771, 144910. <https://doi.org/10.1016/j.scitotenv.2020.144910>
- Nasrollahi, N., Hatami, Z., Taleghani, M., 2017. Development of outdoor thermal comfort model for tourists in urban historical areas; A case study in Isfahan. *Building and environment* 125, 356–372.
- Nevers, C., Carmeliet, J., Kubilay, A., Derome, D., 2026. Heat exposure and cooling efficiency of trees in a tropical hot-humid neighborhood with a park. *Sustainable Cities and Society* 137, 107122.
<https://doi.org/10.1016/j.scs.2026.107122>
- Nikolopoulou, M., Steemers, K., 2003. Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy and Buildings, Special issue on urban research* 35, 95–101. [https://doi.org/10.1016/S0378-7788\(02\)00084-1](https://doi.org/10.1016/S0378-7788(02)00084-1)
- Oh, W., Ooka, R., Nakano, J., Kikumoto, H., Ogawa, O., Choi, W., 2020. Development of physiological human model considering mist wettedness for mist-spraying environments. *Building and Environment* 180, 106706.
- Parkinson, T., De Dear, R., 2015. Thermal pleasure in built environments: physiology of alliesthesia. *Building Research & Information* 43, 288–301.
<https://doi.org/10.1080/09613218.2015.989662>
- Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences* 11, 1633–1644. <https://doi.org/10.5194/hess-11-1633-2007>
- Santamouris, M., Ding, L., Fiorito, F., Oldfield, P., Osmond, P., Paolini, R., Prasad, D., Synnefa, A., 2017. Passive and active cooling for the outdoor built environment—Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. *Solar Energy* 154, 14–33.
- Su, M., Hong, B., Su, X., Liu, A., Chang, J., 2022. How the nozzle density and height of mist spraying affect pedestrian outdoor thermal comfort: A field study. *Building and Environment* 215, 108968.
- Su, X., Luo, Y., Zhang, L., 2025. The synthetical effects of passive radiative cooling building envelopes and surrounding buildings on building daylighting and

- energy performance: A case study in Miami. *Sustainable Cities and Society* 121, 106190. <https://doi.org/10.1016/j.scs.2025.106190>
- Taleghani, M., 2018. Outdoor thermal comfort by different heat mitigation strategies- A review. *renewable and sustainable energy reviews* 81, 2011–2018.
- Taleghani, M., Berardi, U., 2018. The effect of pavement characteristics on pedestrians' thermal comfort in Toronto. *Urban climate* 24, 449–459.
- Tanabe, S., Kobayashi, K., Nakano, J., Ozeki, Y., Konishi, M., 2002. Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD). *Energy and Buildings* 34, 637–646.
- Thorsson, S., Lindberg, F., Eliasson, I., Holmer, B., 2007. Different methods for estimating the mean radiant temperature in an outdoor urban setting. *International journal of climatology* 27, 1983–1994.
- Tomasi, M., Nikolopoulou, M., Giridharan, R., Löve, M., Ratti, C., 2024. Dynamic analysis of a pedestrian network: The impact of solar radiation exposure on diverse user experiences. *Sustainable Cities and Society* 112, 105631. <https://doi.org/10.1016/j.scs.2024.105631>
- Ulpiani, G., 2019. Water mist spray for outdoor cooling: A systematic review of technologies, methods and impacts. *Applied energy* 254, 113647.
- Ulpiani, G., Zinzi, M., 2023. Experimental assessment of the heat mitigation potential of an urban cooling shelter: Combining water misting with solar shading, wind shield, and smart control. *Energy and Buildings* 299, 113623. <https://doi.org/10.1016/j.enbuild.2023.113623>
- VDI 3787 Blatt 2 - 2008-11 - DIN Media [WWW Document], n.d. URL <https://www.dinmedia.de/en/technical-rule/vdi-3787-blatt-2/110541685> (accessed 2.4.26).
- Wang, J., Li, Q., Zhu, G., Kong, W., Peng, H., Wei, M., 2024. Recognition and prediction of elderly thermal sensation based on outdoor facial skin temperature. *Building and Environment* 253, 111326. <https://doi.org/10.1016/j.buildenv.2024.111326>
- Wei, Y.-Y., Cheng, C.-Y., Lin, T.-P., 2025. The influence of trees shade level on human thermal comfort and the development of applied assessment tools. *Landscape and Urban Planning* 263, 105436. <https://doi.org/10.1016/j.landurbplan.2025.105436>
- Wu, H., Jin, R., Liu, M., Nie, Z., Zhao, H., Yao, L., Zhao, L., 2024. Investigating the potential of street trees in mitigating pedestrian thermal stress during heatwaves conditions: An empirical study in Guangzhou. *Building and Environment* 265, 111955. <https://doi.org/10.1016/j.buildenv.2024.111955>
- Wu, H., Zhao, H., Nie, Z., Yao, L., Zhao, L., 2025. Pedestrians thermal responses under variable exposure conditions during heatwaves. *Sustainable Cities and Society* 131, 106703. <https://doi.org/10.1016/j.scs.2025.106703>
- Xie, X., Sun, Z., Zhu, X., Zhao, S., Wang, Z., Zhai, Y., 2024. Influence of misting system on the thermal environment and thermal comfort of seated people in

- semi-outdoor space in Xi'an, China. *Frontiers of Architectural Research* 13, 668–681.
- Yang, J., Liang, Y., Zhong, Z., Dharmasastha, K., Xie, Y., Niu, J.L., 2024. Thermal comfort investigation of membrane-assisted radiant cooling in outdoor settings. *Sustainable Cities and Society* 113. <https://doi.org/10.1016/j.scs.2024.105634>
- Yeom, D.J., Delogu, F., 2021. Local body skin temperature-driven thermal sensation predictive model for the occupant's optimum productivity. *Building and Environment* 204, 108196. <https://doi.org/10.1016/j.buildenv.2021.108196>
- Zhang, M., Xu, C., Meng, L., Meng, X., 2021. Outdoor comfort level improvement in the traffic waiting areas by using a mist spray system: An experiment and questionnaire study. *Sustainable Cities and Society* 71, 102973. <https://doi.org/10.1016/j.scs.2021.102973>
- Zhao, Y., Zhao, K., Zhang, X., Zhang, Y., Du, Z., 2024. Assessment of combined passive cooling strategies for improving outdoor thermal comfort in a school courtyard. *Building and Environment* 252, 111247.