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Tiantian Xu[a,b], Runming Yao[a,b,c]*, Chenqiu Du[a,b], Xizhen Huang[c]

[a] Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing 400045, China

[b] National Centre for International Research of Low-carbon and Green Buildings (Ministry of Science and Technology), Chongqing University, Chongqing 400045, China

[c] School of the Built Environment, University of Reading, Reading, RG6 6DB, UK

***Corresponding author**:

Runming Yao

E-mail addresses: *r.yao@cqu.edu.cn; r.yao@reading.ac.uk*

Full postal address: Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing 400045, China;

Abstract

Heat stress events in urban areas are increasing as a result of global warming and urban heat islands. In response to heat stress, outdoor activators naturally often move themselves to a less hot place. An understanding of human physiological responses in dynamic outdoor thermal environments is desired. This study aims to reveal the dynamic physiological adjustment and thermal perception response characteristics under varying outdoor heat stress conditions. A robust model for predicting dynamic thermal sensations outdoors has been developed. Experiments involving heat stress changes in a hot summer were conducted with 25 subjects. Three categories of data were collected including meteorological data, physiological parameters, and thermal perception. The results showed that lower-arm skin temperature ($T_{lowerarm}$) is more sensitive to changes in the outdoor thermal environment, and correlates closely with the thermal sensation vote (*TSV)*. For a better practical application, based on the strong linear relationship between $T_{lowerarm}$ and T_{ty}, the new dynamic outdoor thermal sensation model has been developed involving two parameters: $T_{lowerarm}$ and T_{ty}. The validity of the model in transient outdoor conditions was verified. The algorithm can be integrated into a wearable armband to predict practical thermal sensation responses. This contribution will advance technologies based on the scientific findings to provide alert services to support human health and wellbeing, consequently increasing urban resilience and sustainability.

Keywords: Dynamic thermal sensation; Urban heat stress; Physiological adjustment; Thermal perception response; Adaptive behavior

Nomenclature

T	Temperature (°C)
RH	Relative humidity (%)
v	Wind speed (m/s)
T_g	Globe temperature (°C)
T_{mrt}	Mean radiation temperature (°C)
$\Delta T/\Delta t$	The change rate of temperature (°C/min)
$\Delta' T$	The difference between the actual and set point value (°C)
TSV	Thermal sensation vote
$OTSV$	Outdoor thermal sensation model

Subscripts

a	air
ty	tympanic
sk	skin
m	mean value
$chest$	the chest part of the human body
$lowerarm$	the lower arm part of the human body
$lowerleg$	the lower leg part of the human body
s	static term
d	dynamic term

1. Introduction

1.1 Background

It is predicted that 68% of the world's population will live in urban environments in 2050 [1]. Urban public spaces accommodate people's outdoor activities forming an important part of cities. People doing recreational and social activities are more likely to stay outdoors when the weather and place are inviting [2]. However, the continuing urbanization exacerbates the Urban Heat Island (UHI) effect. In future, warmer climates due to climate change will cause more frequent excessive heat events. The increased heat stress threat carries significant risks to urban settlements and human health [3, 4]. These trends challenge urban designers to expand their understanding of outdoor thermal comfort and improve the thermal environment of outdoor urban spaces in order to enhance individual health and wellbeing [5].

Thermal discomfort could be an early warning signal for more severe heat-health issues [6]. The hot weather can cause thermal discomfort and negative impacts on public health such as fatigue, dizziness and increased heart rate, a decline in productivity, and chronic outdoor illnesses [7]. Some studies revealed an increase in heat-related mortality when air temperatures reach high values [8, 9]. Concerning its death toll, the most extensively studied extreme weather event was the European heatwaves in 2003. During that summer, the deaths of 70,000 people were associated with excessive heat stress [10].

The alarming danger of climate change has promoted further research on creating the evidence-base for response plans, including heat health messages about different adaptation methods for reducing heat stress [11]. For a given thermal environment, people are no longer passive recipients but instead active agents [12]. The principle underlying thermal adaptation reveals that "*If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*" [13]. Adaptive thermal comfort theory classifies thermal adaptations as physiological adjustment, behavioral adaptation, and psychological adjustment, respectively [12]. In a real environment, people are free to use various adaptive approaches to achieve thermal comfort according to their own thermal preferences. During the hot summer, the adaptation approach focuses on behavioral changes to decrease individuals' levels of exposure to heat stress and to ensure thermal comfort [14], for example, going to a shaded place, wearing a hat, using an umbrella or drinking cold water, etc. Huang *et al.* [15] pointed out that moving to a shaded place is the main adaptation behavior for people to relieve thermal discomfort in summer. This change in environmental heat stress conditions will inevitably lead to changes in physiological and thermal responses. Any physiological changes in response to thermal environmental changes are classified as a physiological adaptations [16]. The change in thermal environment caused by behavioral adaptation will inevitably bring about physiological adaptation, e.g. changes in the body's physiological parameters to re-establish a new thermal balance with the thermal environment [17, 18]. This unsteady state phase of establishing a new equilibrium is called a dynamic adjustment process. In turn, the physiological adjustments can cause changes in a person's subjective thermal perception [19].

Therefore, it is essential to reveal the adaptation mechanism of the human body and to understand how heat stress is affecting the thermal perception and the human physiological response, which is critical for monitoring thermal health and combatting overheating risks in cities. Under the challenges of climate change, it is an urgent need to develop a dynamic model to reflect the relationship between the dynamic characteristics of physiological and thermal responses to varying outdoor heat stress.

1.2 Existing studies of outdoor thermal sensation prediction methods

The thermal sensation is defined as a conscious subjective expression of an occupant's thermal perception of the environment [20] and is often the first step before the estimation of thermal comfort in practice [21]. The existing prediction methods of outdoor thermal sensation can be divided into two categories.

(1) Regression-based on meteorological variables

The type of empirical regression model directly regresses the thermal sensation in terms of environmental and other variables. Various regression models were generated by different studies conducted in different regions. The typical studies include Givoni *et al.* in Japan [22], Nikolopoulou *et al.* involving regression models in five different countries in Europe [23], Spagnolo *et al.* in Australia [24], and many studies in different areas of China [25-27]. These regression models usually consider the environmental parameters (mean radiant temperature, air temperature, relative humidity, global temperature, wind velocity, etc.) as independent variables. Besides environmental parameters, independent variables in the multiple linear regression model increased personal variables (such as clothing insulation and metabolic rate) [28, 29]. The above models simplified the evaluation of outdoor thermal sensation by comprehensively considering the effects of physical, physiological, psychological, social, and cultural factors through a "black box", which is limited to the climate regions where the data was obtained [30].

(2) Thermal indexes based on equivalent temperature

Models are based on the outdoor thermal indices, such as Physiologically Equivalent Temperature (PET), Outdoor Standard Effective Temperature (OUT_SET*), and Universal Thermal Climate Index (UTCI) [31], which are developed from human body heat balance. These thermal indices consider the heat exchange between the human body and the surrounding thermal environment and are sensitive to changes in thermal environmental parameters. However, findings from field studies show deviations in the objective assessment of the thermal index and subjective thermal perception, in which the concept of acclimatization made a tremendous contribution to explaining discrepancies [32]. Thus, many studies have been conducted to establish the relationship between thermal indices and thermal perception in various climate regions to obtain some criteria or benchmarks to assess outdoor thermal comfort [33-35]. But these outdoor thermal sensation models are based on local survey data, which may be limited to different climate regions. For example, the UTCI value range for the neutral range in a tropical climate region is between 19.3°C to 26.7°C [36], whilst the neutral range for a cold climate region is between 14.9°C and 23.2°C [37].

When people are exposed to transient conditions outdoors, these two categories of methods for predicting thermal sensation cannot accurately predict the thermal perception response to thermal environment changes. Most previous studies on dynamic thermal sensation focused mainly on describing indoor dynamic thermal states using physiological properties, quantitatively or qualitatively. For example, Nagano *et al.* [38], Chen *et al.* [39], Xiong *et al.* [40], and Liu *et al.* [41] conducted subject experiments to investigate the thermal response to step changes in temperature in an indoor climate chamber. Generally speaking, the prediction of dynamic thermal sensation can usually be divided into two processes, i.e. obtaining the thermo-physiological and thermal perception responses based on experiments, and developing the dynamic thermal sensation model based on the relationship between thermo-physiological and thermal perception responses [42]. The main typical dynamic thermal sensation models include the dynamic thermal sensation (DTS) model and the University of California, Berkeley (UCB) model, which originated in laboratory studies. The DTS model, proposed by Fiala *et al.,* was developed by correlating experimental thermal sensation votes to various thermo-physiological parameters obtained from simulations with a thermoregulation model [43]. The DTS model depends on the error signal from the mean skin temperature, the error signal from the head core, and the rate of change of the mean skin temperature. The UCB model, proposed by Zhang *et al.,* was developed by building up a regression model between the collected thermal sensation vote, local skin temperature, core temperature, and their change rates [44]. The model integrates both static and dynamic components of thermal sensation predictions, which was originally intended for studying thermal comfort in a non-uniform environment. The data was collected in the experiments with cooling/heating applied locally by custom-made air-sleeves. Beyond that, a TSV model put forward by Takada *et al.* [42] was using regression coefficients to assess scenarios with transient conditions only based on skin temperature and its change rate. In Lai's experiments [45], subjects walked from an indoor to an outdoor environment. The model uses the thermal load, the mean skin temperature, and its change rate to consider dynamic changes in the thermal state of the human body. In terms of mean skin temperature calculated by multiple local skin temperatures, it is inconvenient to obtain the mean skin temperature and its change rate outdoors. These above-mentioned models use the dynamic thermo-physiological parameters to predict the thermal sensation, which allows the assessment of both steady-state and transient conditions.

1.3 Research gap and the objective

In contrast with steady and relative homogenous indoor climates, the outdoor and indoor radiation and wind environments are obviously different. Solar radiation and long-wave radiation can significantly increase the human thermal load, and more changeable winds affect the heat loss by convection and evaporation, all of which affect people's judgment of thermal sensation. Because of the adaption behaviors outdoors, people regularly experience changes in the degree of heat stress [5]. The dynamic thermal sensation models indoors provide a solid physiological and physical foundation for relevant research. However, these models were developed based on data from mimicked thermal environments in laboratories with specifically designed scenarios. Whether these models developed from indoor data can directly predict the dynamic thermal sensation outdoors needs further discussion. Changes in outdoor thermal environments resulting from adaptation behaviors to relieve urban heat stress have yielded few studies on the relationship between dynamic physiological response and thermal perception. Moreover, an effective method of predicting outdoor dynamic thermal perceptions based on physiological parameters is lacking.

In order to express the change of thermal sensation directly from the physiological level, this study aims to develop a dynamic thermal sensation model based on the relationship between dynamic physiological response and thermal perception. The aim is achieved through the following three objectives: 1) to reveal the physiological adaptation mechanism of the human body and the thermal response under varying transient heat stress conditions; 2) to explore the relationship between dynamic response characteristics of physiological parameters and outdoor thermal perception, and 3) to develop a dynamic thermal sensation model based on the relationship between physiological and thermal perception responses. The dynamic model can directly reflect the relationship between human physiological parameters and thermal perception, to obtain the current thermal state of the human body. The effect of outdoor heat stress on thermal perception was evaluated from the perspective of physiological adaptation. This can provide early overheating risk alerts for people undertaking activities outdoors and expand urban designers' understanding of outdoor thermal comfort to establish evidence-based outdoor spaces conducive to health.

2. Methodology

To collect data which reveals the physiological and thermal perception responses to changes in urban heat stress conditions to develop the dynamic outdoor thermal sensation model, human subject experiments were conducted in actual outdoor environments. Based on the main outdoor adaptation behavior, i.e. moving from sunlit to shaded spaces, three shaded scenarios were used as the changing environments for exposure in this study. Three categories of data were collected in these experiments: meteorological data (air temperature, relative humidity, wind velocity, and globe temperature), physiological parameter responses (local skin temperatures and tympanic temperature), and thermal perception (thermal sensation vote). The research framework of this study is shown in Fig. 1. It contains three steps: (1) the data collection based on the main adaption behavior; (2) the exploration of response characteristics of physiological parameters and thermal perception, and the relationship between them; and (3) the development of an outdoor dynamic thermal sensation model. The following section elaborates on the experimental design, experimental procedures, data collection, and statistical analysis.

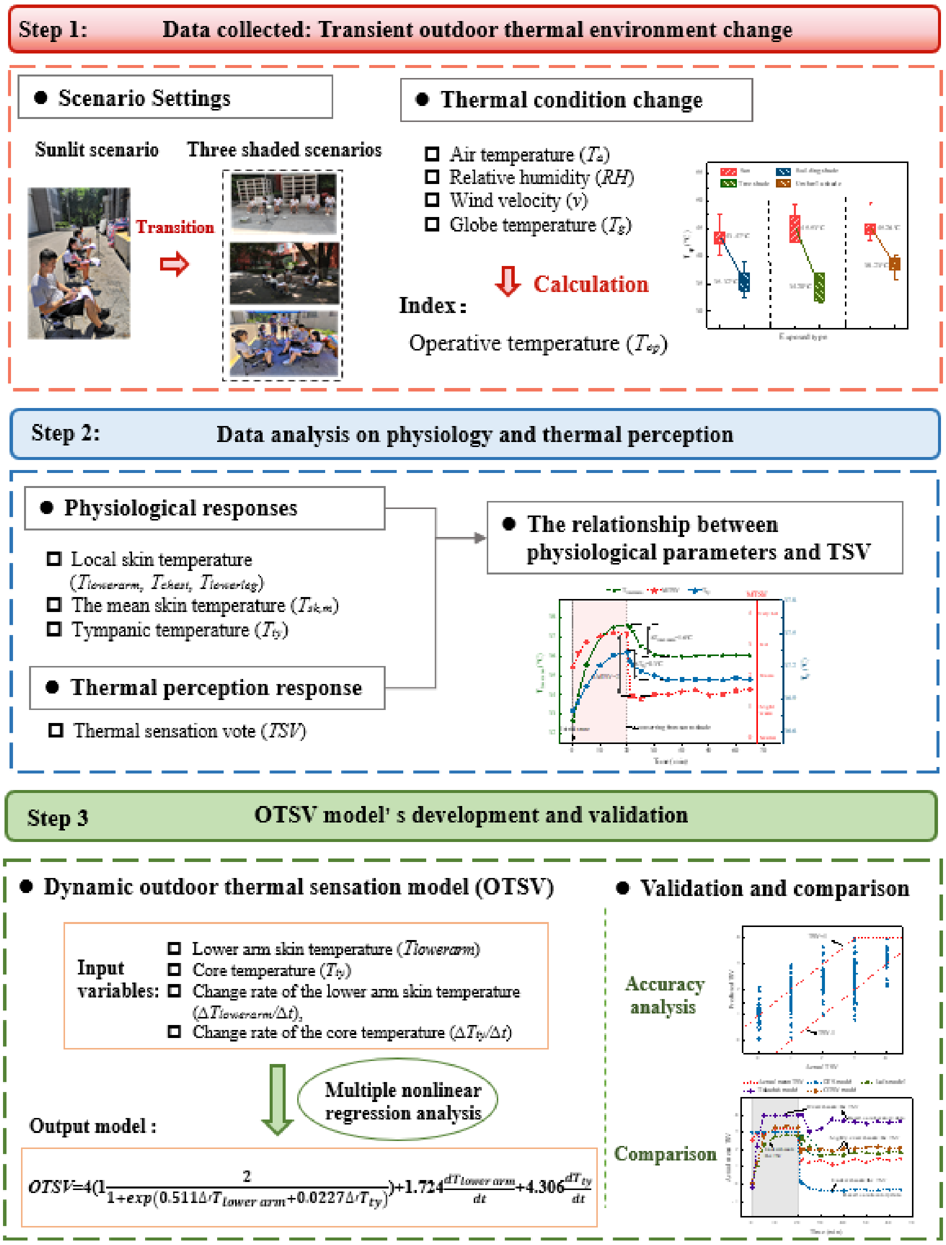

Fig. 1: The conceptual framework of this study

2.1 Experimental design

Chongqing (106°28’, 29°35’) is located in Southwest China, which is a typical representative city with a hot summer. Days with an air temperature above 35°C are mainly in July and August [46]. Compared to winter, high outdoor air temperature and intense solar radiation in summer can cause greater outdoor thermal discomfort to humans. Based on the main outdoor adaption behavior in summer, changes in the thermal environment scenes from sunlit to shaded spaces were reproduced to explore the physiological and thermal response characteristics of people in transient outdoor scenarios. In urban areas, the shading strategies mainly include trees, buildings, and shading devices [47], therefore, different shading situations were designed accordingly. Additionally, in outdoor activities, recreational and social activities, such as sitting, stopping, or standing around enjoying life, would indicate a higher quality of the physical environment that favours people staying outdoors [2]. Hence, relatively static behaviors are adopted in experiments for mimicking these activity types. The one-site experiments were conducted on the campus of Chongqing University under different thermal exposure conditions, as shown in Fig. 2. The scenarios of thermal condition transitions experienced by the subjects are shown in Fig. 3, i.e. moving from a preparation room to an outdoor space in sunlight and then to different shaded spaces, including building ~~tree~~-shaded, ~~building~~tree-shaded or umbrella-shaded spaces. These experiments were all conducted in cloudless weather from July 10, 2019, to August 24, 2019.

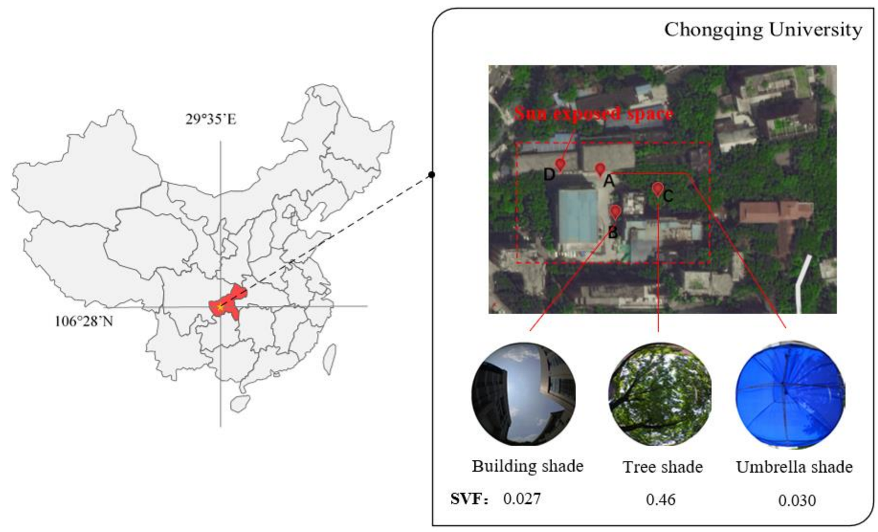

Fig. 2: Study site locations and measured spaces

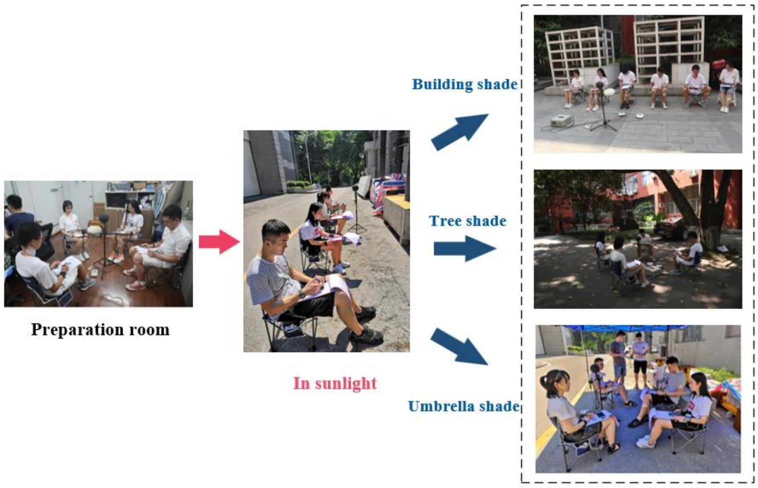

Fig. 3: The scenarios of the thermal condition transitions experienced by subjects

Before the formal experiment, a prior power analysis had been carried out using G*power to determine the sample size. G*power is an independent power analysis program for many statistical tests in the field of social, behavioral, and biomedical sciences [48]. During computation, according to recommended values, the effect size was assumed to be 0.4, the significance level α was set at 0.05, and the power level was set to 0.8. The minimum number of subjects was 15. Some relevant studies have used 8 to 22 subjects [49-51]. During recruiting, the subjects were required to have been in Chongqing for more than one year and to be in good health with no colds, fever, or other symptoms. The experiment enrolled a total of 25 healthy subjects (13 males and 12 females). The detailed information on the physical characteristics of the subjects is summarized in Table 1.

Table 1: Information on the physical characteristics of the subjects

Gender	Number	Age	Height (cm)			Weight (Kg)		
			Min	Max	Average	Min	Max	Average
Male	13	23-28	168	180	172.8	55	83	67
Female	12	22-30	156	168	162.3	49	62	51.2

2.2 Experimental procedure

Prior to commencing the experiment, the subjects were informed of the research objectives and procedures. Each subject signed a consent form before participating in the experiments. In all experimental cases, the subjects maintained a sedentary position and were requested to wear a white T-shirt, shorts, and shoes. The thermal resistance of the whole clothing combination is between 0.28 and 0.32 [20]. Each subject participated in all experiments involving different thermal environment transitions.

Before the subjects went outdoors, they were taken to a preparation room with an ambient temperature close to the neutral level (26°C), and skin temperature logger sensors were attached to body parts. This was followed by an acclimatization stage lasting 30 min to achieve a neutral thermal state [52]. At the end of that time, subjects were asked to fill in the subjective questionnaire. After the evaluation, the subjects immediately moved from the preparation room to the sunlit space and resumed the activities in which they were previously engaged. The parallel evaluation of *TSV* and core temperature measurement of subjects were conducted at 0, 2, 5, 10, 15, and 20 min after the instantaneous environment change. Note that at the sun exposure phase, the sensor measuring skin temperature was always properly attached to the body segments exposed to sunlight. Then, the subjects walked to the tree-, building- and umbrella-shaded spaces. Similarly, they filled in the questionnaire at the shading exposure time (i.e. 0, 2, 5, 10, 15, 20, 25, 30, 35, 40 and 45 mins). The total duration of each experiment was 65 min. Fig. 4 presents the details of the experimental procedure. Since the walking distance between sunlit and shaded spaces was very short, the influence of the walking activity was ignored in this study.

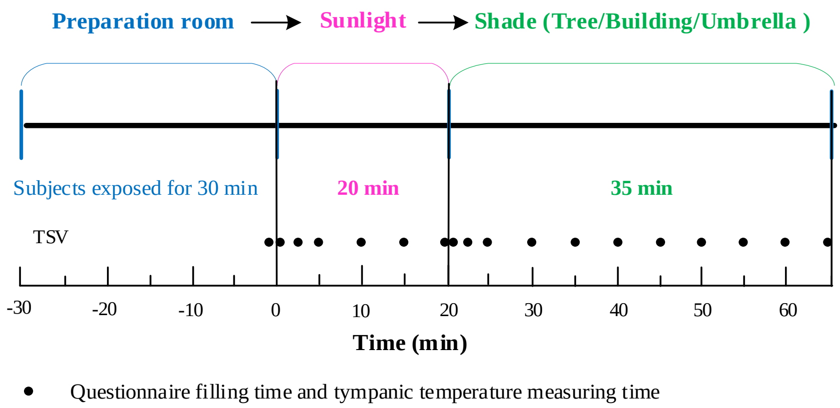

Fig. 4: Details of the experimental procedure

2.3 Data collection

During the subject tests, several parameters of the outdoor thermal environment including air temperature (T_a), relative humidity (RH), wind speed (v), and globe temperature (T_g) were continuously recorded by mini weather stations. Measurements were taken at 20s intervals. The resolution and accuracy of the instruments for each parameter are compliant with the ASHRAE 55 [20] and ISO 7726 standards [53]. Detailed information on the instruments used in the experiment is given in Table 2. These environmental parameters were installed at 0.6m above the ground, which corresponds to the Centre of gravity of a seated person [54].

Physiological parameters including skin temperature and core temperature were measured. Local skin temperatures of body parts were divided into three groups: the core group (including forehead and chest), the intermediate group (including upper leg and lower leg), and the distal group (including lower arm, back of the hand, and instep), based on their positions in the human thermoregulation system and thermal sensation model [44, 50]. In order to avoid the effect on the thermal sensation of wearing too many measuring devices and the inconvenience of transferring between outdoor scenarios, local skin temperature was measured at three body parts: the chest, lower arm, and lower leg, which belong to the core, intermediate, and distal group respectively. According to the experiment results in previous studies, the mean skin temperature outdoors can be obtained by weighting local skin temperature measured from the 3 points above [55-57]. During the experiments, the skin temperature (T_{sk}) of the subjects at their chest, left lower arm and left lower leg were measured continuously. During the measurement, the thermocouples were linked to a multi-channel data collector with an internal reference junction. The skin temperatures can be automatically recorded through the data collector at 10s intervals. The mean skin temperature ($T_{sk,m}$) can be calculated by [57]：

$$T_{sk,m} = 0.5\ T_{chest} + 0.14\ T_{lowerarm} + 0.36\ T_{lowerleg} \qquad (1)$$

Body core temperature refers to the temperature of deep body tissues such as the heart, lung, brain, viscera, etc. Deep-body temperature is not easy to measure but can be generally expressed by rectal, axillary, oral, and tympanic temperature readings. Rectal temperature is reliable and stable, and less affected by external changes [58], but it is often less preferred as it is uncomfortably invasive [59]. The primary limitation of the oral temperature is the evaporative cooling of the buccal cavity accompanying breathing and susceptibility to the effects of drinking [60]. The average axillary temperature is lower than the oral temperature, is susceptible to sweating and takes a long time to measure. The tympanic temperature is closest to the hypothalamus (body temperature regulating Centre), which is supplied with blood from the carotid artery. Therefore, the tympanic temperature is often used as an indicator of brain tissue temperature [61]. The normal value range of these four different measuring sites for deep-body temperature is shown in Fig. 5. It can be seen that the normal range for oral temperature was 33.2-38.2°C, rectal was 34.4-37.8°C, tympanic was 35.4-37.8°C, and axillary was 35.5-37.0°C, respectively.

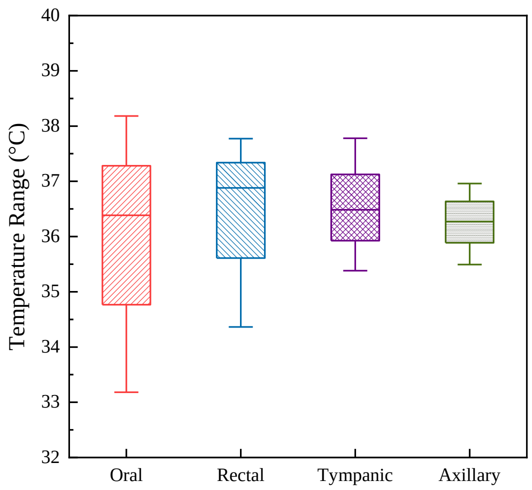

Fig. 5: The normal range of oral, rectal, tympanic and axillary temperature for humans [62]

The tympanic temperature is often used as the body core temperature index given its easier, less intrusive, measurement and rapid dynamic response to thermal transitions [63, 64]. By measuring the tympanic temperature, Yelin Ko *et al.* [63] studied the changes in body core temperature during sleep. Through the comparison with rectal temperatures at various depths, Lee *et al.* [65] verified the validity of the tympanic temperature as a thermal index to evaluate the heat strain experienced by workers in hot environments. Thus, this paper chose the tympanic temperature to measure body core temperature. A Braun IRT-6520 infrared thermometer provided measurements with good accuracy and precision [66] and provided the most convenient and feasible method of obtaining the deep-body temperature outdoors. The detailed information on the instruments used is shown in Table 2.

Table 2: Instruments for measuring environmental and physiological parameters

Parameter	Instrumentation	Range	Accuracy	Interval
Air temperature	Onset Hobo, UX100-011A	-20 to 70°C	±0.21℃	20s
Relative humidity	Onset Hobo, UX100-011A	1 to 95% RH	±2.0 % RH	20s
Wind velocity	WWFWZY-1	0.05 to 30 m/s	5%±0.05 m/s	20s
Globe temperature	HQZY-1	-20 to 80°C	±0.3°C	20s
Skin temperature	TMC6-HD, UX120-006M	-40 to 100°C	±0.5°C	10s
Tympanic temperature	Braun IRT-6520	0 to 50°C	±0.2°C	/

Considering the outdoor extreme hot conditions, the ASHRAE 7-point sensation scale is extended to 9-point by adding additional two points of −4 (very cold) and very 4 (very hot), which is mostly used in this study. This 9-point scale can adequately describe the thermal sensation characteristics in outdoor environments: −4 (very cold), −3 (cold), −2 (cool), −1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), 3 (hot), 4 (very hot) [26, 67].

2.4 Statistical analysis

During the outdoor experiment, the skin temperature sensor may drop due to subjects moving from a sunlit to a shaded space. The subjects were asked to fill out the questionnaires at different times as above-explained in Section 2.2. The data of subjects whose data are missing in the unsteady stage are eliminated. A total of 1,088 valid questionnaires and the corresponding skin temperature (including the local and mean skin temperatures) and core temperature were obtained. Table 3 shows the details of valid subjects' participation and the number of questionnaires collected in each experimental scenario.

Table 3: The detail of valid subjects' participation and the number of questionnaires collected in each experimental scenario

Condition	Scenario 1	Scenario 2	Scenario 3
Subjects	20 subjects (11 males and 9 females)	23 subjects (12 males and 11 females)	21 subjects (11 males and 10 females)
Questionnaire number	340	391	357

Note: Scenario 1: Sunlight to building shade; Scenario 2: Sunlight to tree shade; Scenario 3: Sunlight to umbrella shade.

The variations in the skin and core temperature and the subjective vote were tested for normality using the Shapiro-Wilk test. The relationship between local skin temperature and thermal sensation was analyzed using the Spearman correlation coefficient. The data were divided into two parts: 18 subjects (9 males and 9 females) were selected to establish the model, which met the minimum requirement of 15 subjects; and 7 subjects were selected to verify the accuracy of the model. Regressions were conducted to explore the relationship between dynamic outdoor thermal sensation and the physiological parameters, including the fitting of linear and nonlinear regression equations and the calculation of the correlation index.

The operative temperature (T_{op}), which considers the effects of air temperature, mean radiation temperature, and air velocity, is calculated by the following equation [68]:

$$\mathrm{T}_{op} = \frac{h_c T_a + h_r T_{mrt}}{h_c + h_r} \qquad (2)$$

The radiative heat transfer coefficient, h_r and the convective heat transfer coefficient, h_c, are shown by the following equations [20, 68]:

$$h_r = 4\varepsilon\sigma \frac{A_r}{A_D}\left(273.15 + \frac{T_{cl}+T_{mrt}}{2}\right)^3 \qquad (3)$$

$$h_c = 3.36 + 6.86 v^{0.92} \qquad (4)$$

wherein, ε is the emissivity rate of the globe (typically 0.95), σ is the Stefan-Boltzmann constant, 5.67×10^{-8} W/(m^2·K^4), the ratio A_r/A_D is 0.70 for a sitting person, T_{cl} and T_{mrt} are the mean temperatures in °C of the outer surface and the mean radiation temperature, respectively, and v is the wind velocity, *m/s*.

T_{mrt} is an important parameter in biometeorology and thermal comfort study [69], as one of the necessary parameters for the calculation of T_{op}. The mean radiation temperature was estimated according to the equation [53]:

$$\mathrm{T}_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.1\times10^8 v^{0.6}}{\varepsilon D^{0.4}} \times \left(T_g - T_a\right)\right]^{1/4} - 273.15 \qquad (5)$$

wherein, T_g and T_a are globe temperature and air temperature, respectively, °C and D is the diameter of the black globe sensor, *m*.

3. Results

3.1 Outdoor environment parameters

The average *Ta* in the sunlit space (SS) was highest, followed by the umbrella-shaded (US) space, and the building-shaded (BS) space and the average value in the tree-shaded (TS) space was lowest, see Table 4. Although sunlight is shielded by buildings, trees, and umbrellas, the cooling effects were different. The stronger cooling effect under trees can be explained by better interception of solar radiation all day and transpiration from vegetation. The average *RH* is similar in these four spaces and within the range of 20% to 60%. In the SS and US spaces, the average v values were highest, which we attribute to the spatial characteristics. The two spaces consist of a long and exposed space from east to west, forming a ventilation corridor. The average v in TS space was the lowest, which was attributed to plant cover in the surrounding area and relatively poor ventilation. The average T_g in each space is similar to that of the average T_a. Shading measures adjust the level of exposure to the sky to improve thermal environments, which can be evaluated using the sky view factor (SVF) [70]. It can be seen that the SVF is smaller in the TS space than in the BS space (Fig. 2), which may be the reason that the average T_g in the TS space is lower than that in the BS space. The average T_g in the US space is greater than that in the BS space. That may be because there is a high-temperature roof in the US space and more long-wave radiation is received from the roof, wall, and ground. Meteorological parameters are closely related to spatial characteristics, ventilation conditions, and the intercepted long- and short-wave radiation.

Table 4: Measurements of meteorological variables for the different spaces

Parameter		SS	BS	TS	US
Air temperature (°C)	Max	42.98	38.83	36.24	39.56
	Min	34.50	32.56	31.55	35.03
	Average	37.74	34.45	33.65	37.37
Relative humidity (%)	Max	55.10	49.55	55.73	43.44
	Min	24.00	26.23	26.78	25.59
	Average	42.78	39.09	41.36	32.98
Wind velocity (m/s)	Max	2.80	1.30	0.81	1.76
	Min	1.032	0.50	0.26	0.89
	Average	1.40	0.93	0.59	1.37
Globe temperature (°C)	Max	51.25	39.12	37.0	40.26
	Min	41.20	32.44	31.64	35.72
	Average	48.73	35.36	34.22	38.30

Shade can significantly change the outdoor thermal environment and relieve outdoor heat stress. Fig. 6 shows the T_{op} in the sunlit space and different shaded spaces. The colours represent the different thermal conditions. As shown, the T_{op} in the sunlit space ranged from 40.3°C to 49.5°C. The respective temperature ranges for T_{op} in different shaded environments ranged from 32.4°C to 39.1°C for BS space, from 31.7°C to 37.0°C for TS space, and from 35.7°C to 40.2°C for US space. Compared to the T_{op} value in SS space, the average T_{op} in the BS, TS and US spaces was lower by about 8.2°C, 11.3°C and 7.0°C, respectively. Comparing the T_{op} value in TS space and US space, which have a similar SVF, it can be seen that TS space has a better effect on relieving heat stress. Meanwhile, although the SVF of BS space is greater than that of US space, the BS space also has a better ability to relieve thermal stress. The smaller SVF in the TS space may be one of the reasons why the TS space offers a better heat stress relief effect than the BS space.

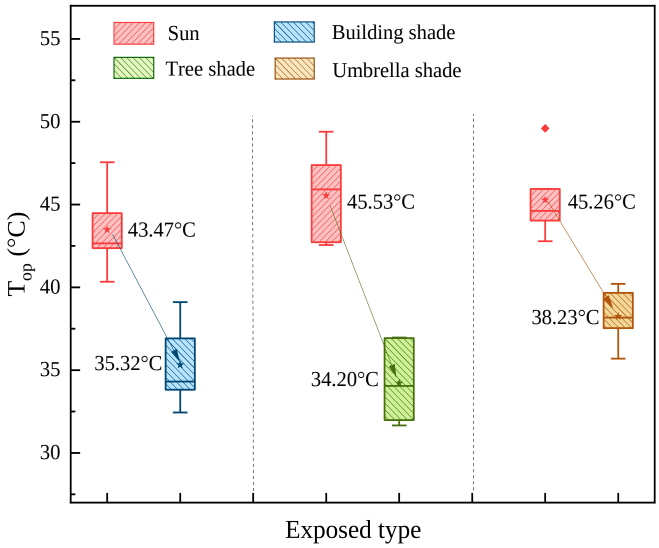

Fig. 6: The T_{op} in the sunlit space and different shaded spaces

3.2 Physiological and psychological responses of subjects

The changes in local skin temperatures, i.e. chest, lower leg, and lower arm and the mean skin temperature for all subjects when the outdoor thermal environment was converted are shown in Fig. 7. The boxplot is used to represent the distribution of data, and the dotted lines in different colours show the trend of the average values for the mean and local skin temperatures. In the paper, the unsteady state phase of establishing a new equilibrium is called the dynamic state, in which skin temperature or core temperature still increases or decreases. If the change is small enough over time, skin temperature or core temperature could be considered as reaching a steady-state, similar to Ji *et al.* [71]. As shown, the tendency of local skin temperatures is the same, but the maximum value and the steady value of local skin temperatures in different body parts are different. In the preparation room, the average T_{chest} is the highest at around 34°C with the average $T_{lowerleg}$ and $T_{lowerarm}$ being about 1.5°C lower. The average value of $T_{sk,m}$ for all subjects is about 33°C. After entering the sunlit space, the $T_{lowerleg}$ and $T_{lowerarm}$ increase rapidly and stabilize at about 36.8°C and 37.5°C, respectively. T_{chest} increases more slowly and decreases slightly after reaching a maximum of 36.4°C. When subjects move to shaded spaces, the average T_{chest}, $T_{lowerleg}$, and $T_{lowerarm}$ decrease quickly reaching steady values of about 34.8°C, 35.7°C and 36.2°C, respectively. The

$T_{sk,m}$ increases logarithmically and reaches a relatively stable temperature (36.5°C) when subjects move to the sunlit space. The $T_{sk,m}$ increases by about 3℃ for subjects. When converting from sunlit space to shaded space, the $T_{sk,m}$ gradually decreases and becomes relatively stable at 35°C.

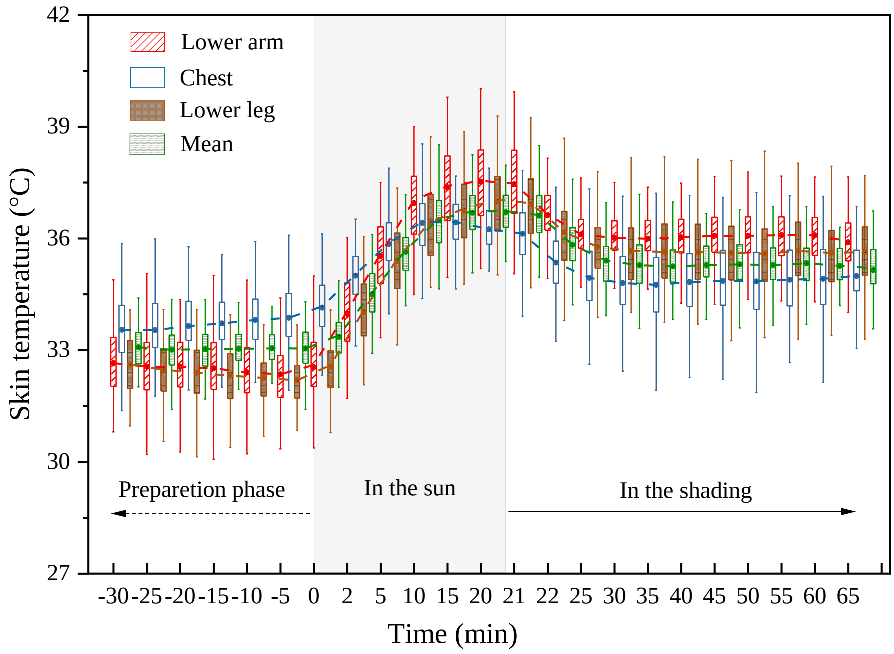

Fig. 7: The changes in measured local skin temperatures and the mean skin temperature when the outdoor thermal environment changes.

Fig. 8 shows the change rate in measured local skin temperatures and the mean skin temperature when the outdoor thermal environment is converted. A positive number represents an increase in skin temperature and a negative number represents a decrease. The change rate value is maximum at the beginning of the thermal condition change and is related to the temperature difference between the thermal conditions experienced before and after the change. It can be seen clearly that when the thermal condition changes, the change rate of $T_{lowerarm}$ is the largest, followed by $T_{lowerleg}$, and T_{chest}, which is the smallest change rate. This indicates that the skin temperature of the lower arm in the distal group is more responsive to the dynamic outdoor thermal environment, which is easily affected by environmental temperature due to the lower level of blood circulation [72]. Due to the human thermoregulation system, the local skin temperature of the chest in the core group varies within a smaller range.

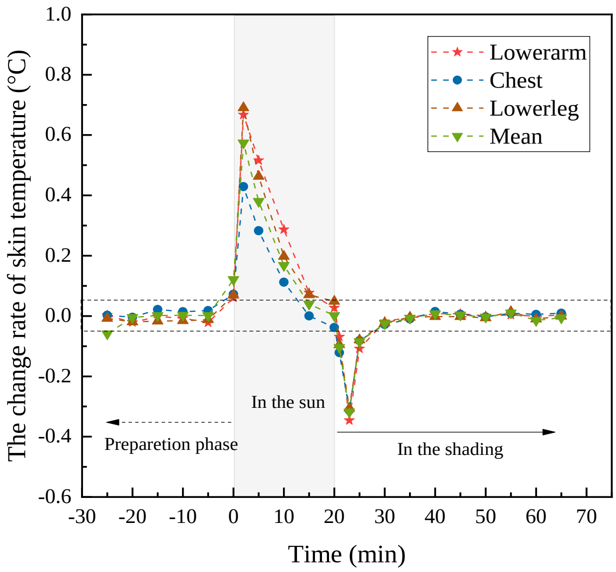

Fig. 8: The change rate in measured local skin temperatures and the mean skin temperature when the outdoor thermal environment changes.

Fig. 9 demonstrates the frequency distribution of *TSV* for all subjects in a sunlit space and different shaded spaces. In sunlit space, the *TSV* is mainly distributed in "Hot" and "Very hot", with the highest *TSV* frequency being "Hot" at about 170. The *TSV* of subjects in building-shaded and tree-shaded spaces is mainly distributed in "Neutral" and "Slightly warm", and the frequency of subjects who considered slightly warm in the current environment is higher. In the umbrella-shaded space, the frequency of subjects who chose "Hot" was the highest, which may be due to the higher temperature under the umbrella. The dotted curves in different colours in Fig. 9 represent the distribution of *TSV* under different heat stress conditions. By comparing the maximum values of the *TSV* distribution curves for the transition to building and tree-shaded space from sunlit space, the maximum values of *TSV* distribution moved two units from "Hot" to "Slightly warm". And with the transition to the umbrella shade, the maximum values of *TSV* distribution moved one unit to "Warm". As a whole, the shaded spaces can significantly relieve outdoor heat stress and improve outdoor thermal comfort.

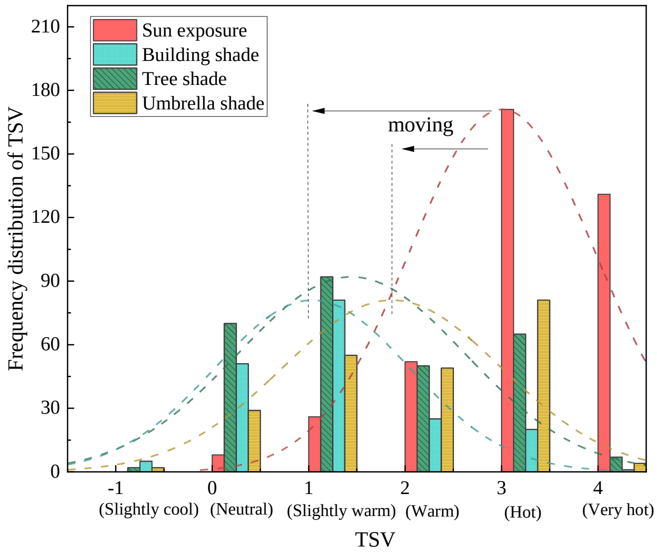

Fig. 9: The frequency distribution of *TSV* for sunlit spaces and different shaded spaces (Note: frequency represents the occurrence number of *TSV* with different scales)

To compare which part of skin temperature is a better description of thermal perception, the Spearman correlation coefficient between the local and mean skin temperatures and thermal sensation were analyzed. The results show that there are significant associations between *TSV* and $T_{lowerarm}$, $T_{lowerleg}$, T_{chest} and $T_{sk,m}$. Spearman coefficient values between overall *TSV* and $T_{lowerleg}$, $T_{lowerarm}$, T_{chest} and $T_{sk,m}$ are 0.276, 0.517, 0.482, and 0.443 respectively, of which the correlation coefficient between $T_{lowerarm}$ and *TSV* is the highest. In addition, when the thermal condition changes, there is a greater skin temperature change rate in the lower arm. This indicates that $T_{lowerarm}$ can be a good potential indicator of thermal state. Similar results are obtained from previous studies [52, 73]. The exposed parts of the body have a higher prediction accuracy for thermal comfort and can provide more useful information on skin temperature and the change rate of skin temperature for outdoor thermal comfort [32]. Fig. 10 depicts the changes in overall mean *TSV* (*MTSV*), the average T_{ty}, and the average $T_{lowerarm}$ over time when subjects converted from a neutral environment to a sunlit space and from a sunlit space to different shaded spaces. It can be seen that when the thermal environment changes, the changing trend among *MTSV*, T_{ty} and $T_{lowerarm}$ are consistent. As a general trend, the *MTSV* increases or decreases significantly and then stabilizes quickly over the exposure time after the thermal environment transition. By comparing the different directions of the conversion (to a sunlit space or a shaded space), it can be seen that the thermal perception of subjects changes more quickly to cold stimuli. The *MTSV* value of subjects in sunlit space in the stable stage is between hot (3) and very hot (4). Comparing the thermal sensation in sunlit and shaded conditions, the different shade strategies can all relieve heat stress and improve outdoor thermal comfort, lowering *MTSV* from "very hot" to "slightly warm" or "warm" in summer. These findings emphasize the benefits of shading in summer, which is in line with previous studies [74-76]. As shown, the T_{ty} increases slowly with time in a narrow temperature range when the subjects are exposed to sunlight. The mean value of T_{ty} changes from about 36.8°C to 37.4°C. When subjects move to shade spaces, the T_{ty} gradually recovers and achieves a new steady level at about 37.1°C. The air temperature in shaded environments is much higher than in the neutral environment in the initial state. This is why the T_{ty} of subjects in shaded spaces is higher than that of the initial T_{ty} at the moment of entering the sunlit space. The initial T_{ty} at the time 0 min can be considered as the T_{ty} indoors. This indicates that the T_{ty} is different for different thermal conditions. When subjects move to a sunlit space, the average $T_{lowerarm}$ changes from about 32.6°C to 37.6°C and the average $T_{lowerarm}$ decreases gradually to 36.0°C after the transition to shading. The shaded environments can decrease the average $T_{lowerarm}$ by about 1.6°C. In the whole process, both the $T_{lowerarm}$ and T_{ty} increase or decrease logarithmically and reach a relatively stable stage after about 15 minutes. The overall trend of *MTSV* and $T_{lowerarm}$ and T_{ty} are similar, while the difference between them is that the *MTSV* changes rapidly and sharply within a short period in shaded spaces, and then tends to be stable, but the $T_{lowerarm}$ and T_{ty} change according to a process of gradual change. In thermoregulation, when a change in the thermal status of the environment registers with the thermoreceptors in the skin, the skin temperature functions as a sensor and delivers the information to the thermoregulatory centre. The gradient between the skin and the core temperature initiates the process of thermoregulation [77].

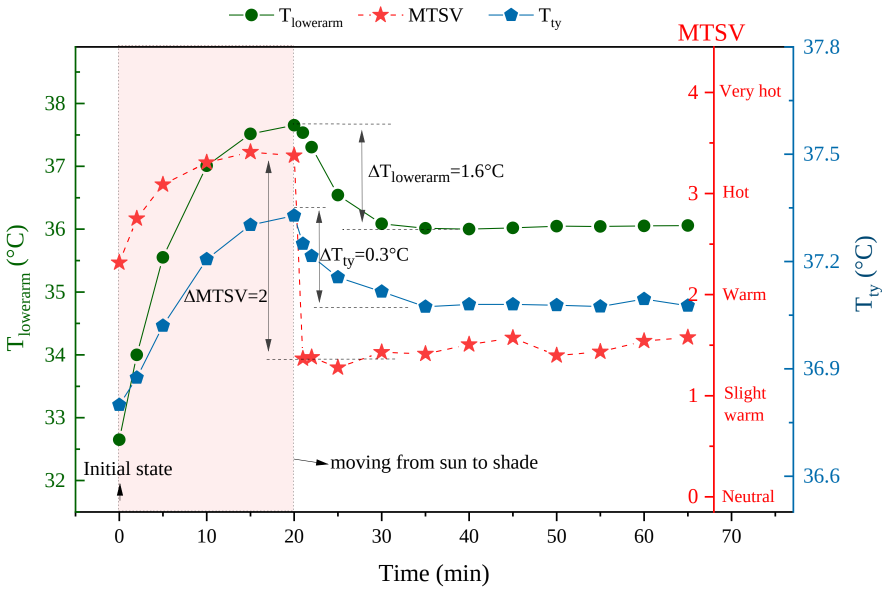

Fig. 10: The subjects' overall MTSV, $T_{lowerarm}$ and T_{ty} in response to the outdoor thermal environment changing (Note: MTSV, $T_{lowerarm}$, and T_{ty} represent mean thermal sensation vote, lower arm skin temperature, and core temperature)

Figs. 11(a) and 11(b) plot the mean *TSV* reported by the subjects in the outdoor spaces when outdoor thermal conditions were converted in each 0.1°C interval group for $T_{lowerarm}$ and T_{ty}. The blue dots stand for the *TSV* values after stabilization, and the orange triangles stand for *TSV* values during unsteady-state conditions. It can be seen that after stabilization, the relationships between the skin temperature and core temperature and outdoor thermal sensation were linear within a certain range. The red dotted lines in Figs. 11(a) and 11(b) are the fitting curves for the relationship between thermal sensation and lower arm skin temperature and core temperature, respectively. Due to the limitation of *TSV* and the regulation mechanism of the human body, the relationship between thermal sensation vote and skin temperature and the core temperature is not always linear. When skin temperature and core temperature exceed a certain value, the vote value approaches the maximum limit. At a steady-state, when the lower arm skin temperature exceeds 37.3°C or the core temperature exceeds 37.5°C, most subjects will feel hot ($TSV > 3$). The points indicated by orange triangles seem to be discrete in Figs. 11(a) and 11(b). Therefore, the lower arm skin temperature and core temperature in unsteady-state conditions cannot directly predict thermal sensation.

Furthermore, it can be seen in Figs. 11(c-f), the relationship between $\Delta T_{ty}/\Delta t$ and TSV is not high but has a good correlation with $\Delta TSV/\Delta t$. Similarly, compared with the correlation between $\Delta T_{lowerarm}/\Delta t$ and TSV, there is a higher correlation between $\Delta T_{lowerarm}/\Delta t$ and $\Delta TSV/\Delta t$. It may thus be appropriate to use the change rate of lower arm temperature and core temperature to predict changes in thermal sensation.

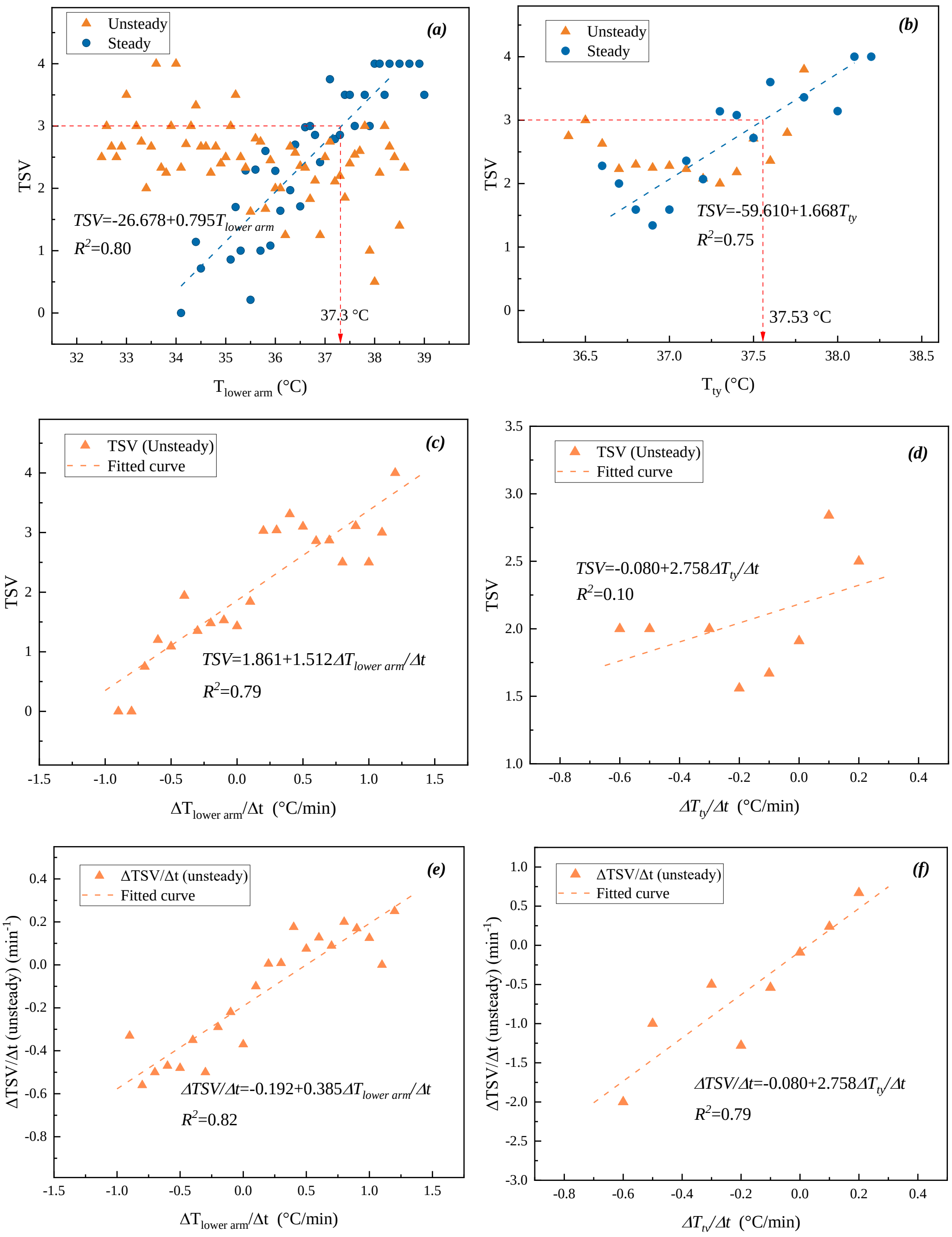

Fig. 11: The relationship between thermal sensation and physiological parameters.

(a) the *TSV* and $T_{lowerarm}$, *(b)* the *TSV* and T_{ty}, *(c)* the *TSV* and $\Delta T_{lowerarm}/\Delta t$, *(d)* the *TSV* and $\Delta T_{ty}/\Delta t$, *(e)* the $\Delta TSV/\Delta t$ and $\Delta T_{lowerarm}/\Delta t$, *(f)* the $\Delta TSV/\Delta t$ and $\Delta T_{ty}/\Delta t$

3.3 Dynamic model for humans in outdoor transient conditions

The stimulation of temperature receptors (skin temperature receptors and core temperature receptors) is a direct factor affecting the change of thermal sensation. Previous relevant studies have shown that the general properties of thermoreceptors include both static and dynamic responses [45, 52, 78, 79]. According to the response characteristics of human temperature receptors after stimulation, the thermal sensation model can be divided into two parts: a static term and a dynamic term [80]. The change rate is a good variable to reflect the dynamic stimulus of temperature receptors [44]. The lower arm skin temperature is a better indicator for predicting the outdoor thermal sensation in this study. Thus, the lower arm skin temperature ($T_{lowerarm}$), the core temperature (T_{ty}), the change rate of the lower arm skin temperature ($\Delta T_{lowerarm}/\Delta t$), and the change rate of the core temperature ($\Delta T_{ty}/\Delta t$) are the predictor variables for determining the outdoor thermal sensation. Among them, the $T_{lowerarm}$ and T_{ty} represent the response value to stable conditions, and $\Delta T_{lowerarm}/\Delta t$ and $\Delta T_{ty}/\Delta t$ capture the dynamic response of thermal sensation under transient conditions. The function can be expressed as:

$$Thermal\ sensation = f\,(T_{lowerarm},\ T_{ty},\ dT_{lowerarm}/dt,\ dT_{ty}/dt) \qquad (6)$$

The static term is used to describe the relationship between thermal sensation and physiological parameters when the human body is in a steady-state condition. Based on previous studies[44, 45] and the analysis above, we found that the logical function can well express the relationship between thermal sensation and predictor variables under steady-state conditions. The general form of the logistic function can be written as:

$$y = A\left(1 - \frac{2}{1+\exp\left(\sum_i B_i x_i\right)}\right) \qquad (7)$$

where A is the limit coefficient and B is the slope coefficient. The relationship between x and y is linear when the value of x is small. As x increases or decreases, the value of y reaches the upper limit of A or the lower limit of $-A$.

The thermal sensation under steady-state conditions is predicted based on the parameter's degree of deviation from the set point. The setpoint value can be determined when the thermal sensation for humans is neutral (zero). Therefore, the thermal sensation model under steady-state conditions (TSV_s) can be expressed as:

$$TSV_s = A(1 - \frac{2}{1+\exp\,(B_1\Delta' T_{lowerarm} + B_2\Delta' T_{ty})}) \qquad (8)$$

where A is the limit coefficient, which represents the thermal sensation range, B_1 and B_2 are the coefficients for the static term. $\Delta' T_{lowerarm}$ is the difference between the actual and neutral lower arm skin temperature, the neutral $T_{lowerarm}$ is 33.56°C, which is obtained by averaging the skin temperature when the subjects voted for a neutral outdoor temperature. $\Delta' T_{ty}$ is the difference between the actual and neutral core temperature, the neutral T_{ty} is assumed to be 36.5°C [52]. When the body's core temperature remains neutral, skin temperature is a good indication of the thermal sensation under steady-state conditions.

The steady-state thermal sensation model can predict steady-state sensation but fails to predict correctly the sensations observed when skin temperature or core temperature rises or falls. The dynamic term (TSV_d) needs to be added to predict thermal sensation in transient conditions. According to Ring and de Dear [81], Zhang *et al.* [44] and Du *et al.* [82], the dynamic portion does not follow the logical curve. There was a linear relationship between thermal sensation and the dynamic response of skin thermal receptors [44]. Therefore, we express the dynamic portion as:

$$TSV_d = C_1\frac{\Delta T_{lowerarm}}{\Delta t} + C_2\frac{\Delta T_{ty}}{\Delta t} \qquad (9)$$

where C_1 and C_2 are the coefficients for the dynamic term.

The dynamic thermal sensation can be expressed as the sum of the static and dynamic terms [44]. Combining the static and dynamic terms above, the dynamic thermal sensation model can be written as:

Dynamic thermal sensation$=TSV_s + TSV_d$

$$=A\,(1-\frac{2}{1+\exp\left(B_1\Delta' T_{lower\ arm} + B_2\Delta' T_{ty}\right)}) + C_1\frac{\Delta T_{lowerarm}}{\Delta t} + C_2\frac{\Delta T_{ty}}{\Delta t} \qquad (10)$$

When the change rate of the lower arm and the core temperatures are zero, the human body is in a steady-state condition, i.e. the dynamic portion of the model is zero, and the thermal sensation can be predicted by the steady-state model.

The static portion (TSV_s) model was obtained by the difference between the actual and the neutral $T_{lowerarm}$ ($\Delta' T_{lowerarm}$), the difference between the actual and neutral T_{ty} ($\Delta' T_{ty}$) and the *TSV* under steady-state conditions. The equation with a correlation coefficient (R^2) of 0.69 can be expressed as:

$$TSV_s = 4\left(1-\frac{2}{1+\exp\left(0.511\Delta' T_{lower\ arm}+0.0227\Delta' T_{ty}\right)}\right) \qquad (11)$$

The TSV_d can be calculated by the value of the difference between the actual thermal sensation vote and TSV_s. Based on the experimental dataset of the thermal sensation, $\Delta T_{lowerarm}/\Delta t$ and $\Delta T_{ty}/\Delta t$ in different thermal transition conditions, the regression equation of TSV_d is produced. Note that at some point, the value of $\Delta T_{lowerarm}/\Delta t$ and $\Delta T_{ty}/\Delta t$ correspond to the TSV_d value in *°C/min*, which was obtained based on the different values of the monitored $T_{lowerarm}$ or T_{ty} divided by the monitoring time interval. The fitted results conformed to a linear relationship with a correlation coefficient (R^2) of 0.88, which can be expressed as:

$$TSV_d = 1.724\frac{\Delta T_{lower\ arm}}{\Delta t} + 4.306\frac{\Delta T_{ty}}{\Delta t} \qquad (12)$$

Based on the static and dynamic terms of the thermal sensation model above, the dynamic outdoor thermal sensation model (*OTSV*) can be described by:

$$OTSV = 4\left(1-\frac{2}{1+\exp\left(0.511\Delta' T_{lower\ arm}+0.0227\Delta' T_{ty}\right)}\right)+1.724\frac{\Delta T_{lower\ arm}}{\Delta t}+4.306\frac{\Delta T_{ty}}{\Delta t} \qquad (13)$$

According to the above analysis of physiological response characteristics, when the thermal environment changes, both $T_{lowerarm}$ and T_{ty} will adjust to adapt to the new environment, and the changes between them have a certain correlation. Fig. 12 presents the relationship between mean $T_{lowerarm}$ and mean T_{ty} at the same time in different transient conditions. It can be seen that in the process of subjects moving from indoors to a sunlit space, both $T_{lowerarm}$ and T_{ty} increase, and in the process of subjects moving from a sunlit to a shaded space, both $T_{lowerarm}$ and T_{ty} decrease together. There is a linear regression relationship between them with a good correlation coefficient. By integrating the two processes, the relationship between mean $T_{lowerarm}$ and mean T_{ty} can be expressed as:

$$T_{ty}=33.47+0.1T_{lowerarm} \quad (R^2=0.96) \tag{14}$$

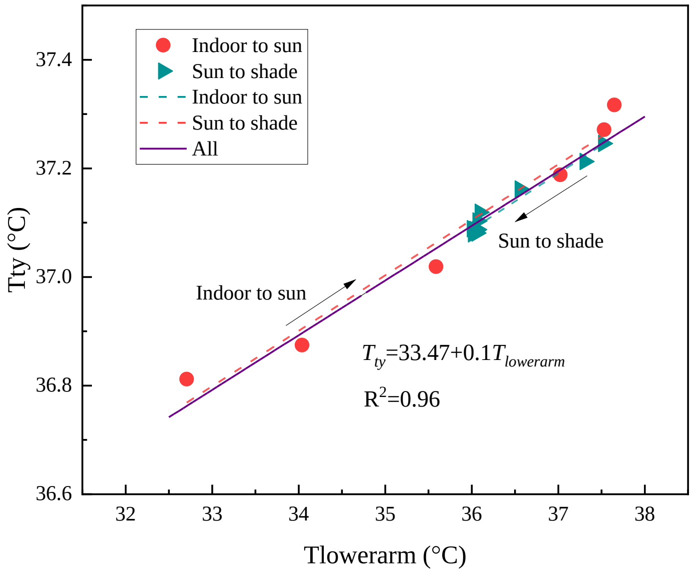

Fig. 12: The relationship between mean $T_{lowerarm}$ and mean T_{ty} at the same time

Based on the strong linear relationship between $T_{lowerarm}$ and T_{ty}, the *OTSV* model can be described by the only variable: $T_{lowerarm}$, as expressed in the following equation:

$$OTSV=4\left(1-\frac{2}{1+\exp\left(0.611\Delta' T_{lowerarm}-3.03\right)}\right)+2.155\frac{\Delta T_{lowerarm}}{\Delta t} \tag{15}$$

The purpose of the conversion from T_{ty} to $T_{lowerarm}$ is to reduce the real-world complications in measurement. The $T_{lowerarm}$ can be measured using a wearable armband or smart armband. The wearable sensor technology embedded with the skin algorithm can provide alerts for overheating risks for people engaging in activities outdoors.

Fig. 13 shows the comparison between actual *TSV* and predicted *TSV* for individuals. Two deviation lines were plotted to show the scattering trend of predicted *TSV*. The results show that 70.2% of the data describe a difference of less than one unit between the predicted and measured thermal sensation. Considering the complexity of the outdoor thermal environment, we consider that these prediction results are acceptable.

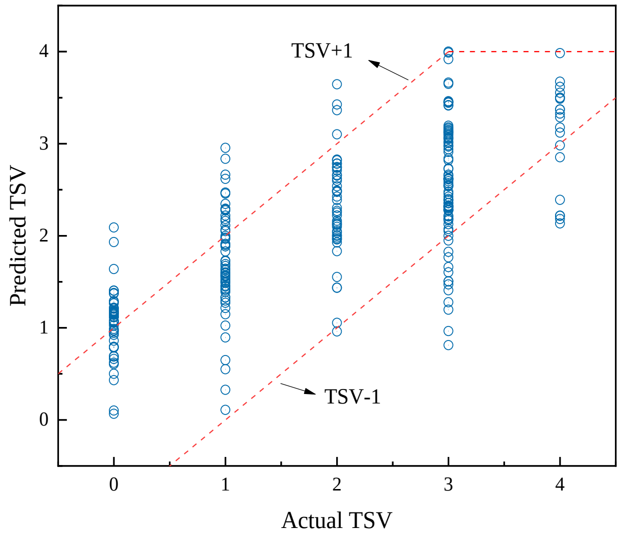

Fig. 13: Comparison between actual TSV and predicted TSV for individuals

4. Discussion

4.1 Sensitivity study

Sensitivity analysis deals with studying the effects of different input variables on the variation of output quantities for any kind of system or model [83]. The sensitivity analysis methods can be divided into local sensitivity analysis and global sensitivity analysis [84] with local sensitivity analysis being the most commonly used due to its high calculation efficiency [85]. Local sensitivity analysis is based on the assumption that the model is expressed as $y=f(x_1, x_2, ..., x_n)$ (x_i is the i^{th} variable value of the model), and each variable changes within the range of possible values to predict how the output value changes according to changes in the input value. The impact of the output value is called the sensitivity influence coefficient (IC) of the variable. IC can be calculated by Equation 16 [86]. There are 4 variables for sensitivity analysis in this study. The range of input variables is shown in Table 5.

$$\mathrm{IC} = \frac{changeinoutput}{changeininput} = \frac{\partial OP}{\partial IP} = \frac{OP-OP_{bc}}{OP_{bc}} \Big/ \frac{IP-IP_{bc}}{IP_{bc}} \qquad (16)$$

The ranges of $\Delta' T_{lowerarm}$, $\Delta T_{lowerarm}/\Delta t$, $\Delta' T_{ty}$, and $\Delta T_{ty}/\Delta t$ vary from 0 to 4 °C, from -1 to 1 °C/min, from 0 to 1.3 °C, and from -0.5 to 0.5 °C/min according to the actual human experiments in a warm environment.

Table 5: Input variables and their ranges for sensitivity analysis.

No.	Variables	Base value	Probability	Range
x1	$\Delta' T_{lowerarm}$	0	Continuous Uniform	[0, 4]
x2	$\Delta T_{lowerarm}/\Delta t$	0	Continuous Uniform	[-1, 1]
x3	$\Delta' T_{ty}$	0	Continuous Uniform	[0, 1.3]
x4	$\Delta T_{ty}/\Delta t$	0	Continuous Uniform	[-0.5, 0.5]

All the sensitivity influence coefficients (IC) of the parameters for dynamic outdoor thermal sensation model were calculated, see Fig. 14. It can be seen that in the transient varying heat stress conditions, the change rate of core temperature has the greatest influence on the output, followed by the change rate of lower arm temperature, lower arm temperature, and the core temperature which has the least influence on the model's outputs.

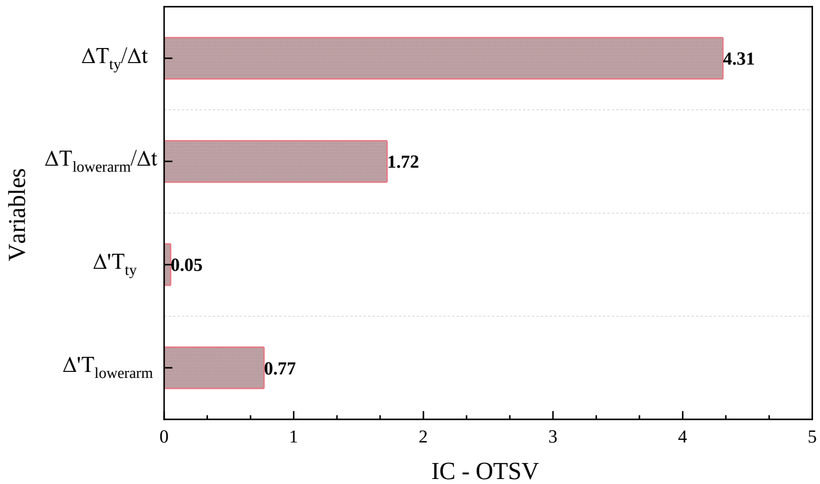

Fig.14: Sensitivity analysis of input parameters for the OTSV model

4.2 Comparison between other dynamic models

Based on the outdoor experimental scenarios, Fig. 15 compares the actual thermal sensation with the sensation predicted by the models of Fiala, Lai, Takada, and *OTSV* (the experiments in this study). The dotted and solid lines in the figure represent the data obtained from indoor and outdoor experiments, respectively. It can be seen that these models correctly reproduced the trend of change, but the values differed considerably. For Fiala's model, when subjects move to a sunlit space, the predicted value of thermal sensation directly increased to the maximum without reflecting the gradual change process compared with the actual thermal sensation. And then the thermal sensation prediction goes with the actual thermal sensation with differences of about 2 units when subjects move to shady spaces, which greatly underestimates the true thermal sensation. For Takada’s model, whether moving to a sunlit or a shaded space, the model overestimates the outdoor thermal sensation. Compared with the two models above, Lai's model predictions are better but still slightly underestimate the thermal sensation of subjects moving into the sunlit space and overestimate the thermal sensation of subjects moving into the shaded space. The underestimation of the thermal sensation in Lai's model in the sunlit space may be caused by different TSV scales adopted. In addition, it does not well-predict the rapid decrease of thermal sensation. The *OTSV* model in this study can well predict the dynamic change process of thermal sensation when subjects are transferred to a sunlit or a shaded environment. After stabilizing in a shaded environment, there is an error of about 0.8 units in predicting thermal sensation, which slightly overestimates the actual *TSV*. This error may be due to psychological factors, such as expectation and thermal experience. Outdoor thermal comfort in an urban environment is a complex issue with multiple layers of concern [87]. Subjective thermal perception is not always consistent with biometeorological conditions. Although there is an error when subjects move to a shaded environment, the predicted thermal sensation is in good agreement with the actual thermal sensation when moving to a sunlit space.

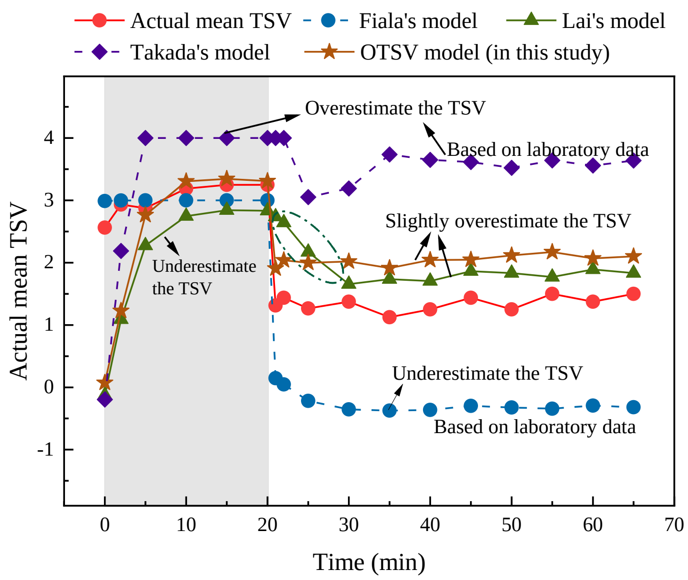

Fig. 15: Comparison of the actual mean thermal sensation votes with the predicted votes for outdoor research.

For the *OTSV* model in this paper, there are three main differences from the other models mentioned above. Firstly, the lower arm temperature, which is easy to obtain, is used as the input variable to predict the outdoor thermal sensation. In the DTS model, Lai's model, and Takada's model, the mean skin temperature and the change rate of the skin temperature were used as predictors for the human thermal sensation. It is very inconvenient to obtain the mean skin temperature and its changes over time when people are outdoors. Based on the current development of portable temperature sensing instruments, such as armbands and smart bracelets, the lower arm skin temperature and its changes outdoors are easier to collect. Therefore, the *OTSV* model has a better prospect of being applied in practice. Secondly, compared with the 7-point *TSV* scale used in the DTS model and Lai's model, an extended 9-point *TSV* scale is adopted in the experiment, adding "very hot" and "very cold" to accommodate extreme environments. It can adequately describe the thermal sensation characteristics in hot outdoor environments. Last but not least, based on the main adaption behavior outdoors, the real outdoor scenarios for experiments were designed considering the solar radiation and natural wind, which cannot be replicated in indoor simulation conditions.

4.3 Limitations and further work

A dynamic outdoor thermal sensation model with convenient measurement of the predictor input variable has been developed. Several limitations are stated here in order to provide an improved interpretation of the results in the current study. Kruger *et al.* [88] noted that anthropometric characteristics, including age, body mass, and skin colour affect thermal judgment. In this study, the subjects did not encompass a wide variety of ages, weights, or other factors. The prediction model of outdoor thermal sensation was established based on the age of the subjects: 22-30 years old. In this paper, physiological adaptation mechanisms and dynamic thermal perception responses under outdoor high temperatures in summer were analyzed. Therefore, the impact of clothing was not considered because its effect is limited in a hot summer [89, 90]. Future studies could be extended to other scenarios using the proposed method and explore the influence of more complicated factors, such as the inhomogeneous radiation in different human body segments, on human thermal response.

5. Conclusions

In order to provide an early warning of overheating risk and ensure the thermal safety of people outdoors, this study developed a dynamic thermal sensation model based on the relationship between the dynamic physiological adjustment process and the dynamic thermal perception response process. Based on the main behavioral adaptation for outdoor heat stress, i.e. moving from a sunlit space to different shaded spaces, a series of experimental conditions in real outdoor scenarios were designed. The experiments on outdoor dynamic thermal sensation involving 25 subjects were conducted in the hot summer in Chongqing, China. Based on the methodology, the effect of outdoor heat stress on thermal perception evaluated from the perspective of physiological adaptation was revealed, and a new outdoor dynamic thermal sensation model was developed. The main conclusions drawn include the following:

(1) The static portion (TSV_s) of the dynamic thermal sensation model can be described by a logistic function, based on $T_{lowerarm}$ and T_{ty}. The dynamic portion (TSV_d)

built by the $\Delta T_{lowerarm}/\Delta t$ and $\Delta T_{ty}/\Delta t$ was added to account for and predict real-time changes in thermal sensation. For a better practical application, based on the strong linear relationship between $T_{lowerarm}$ and T_{ty}, the new dynamic outdoor thermal sensation model has been developed involving two parameters: $T_{lowerarm}$ and T_{ty}.

(2) Local skin temperature at the distal part directly exposed to the environment is more sensitive to changes in the outdoor thermal environment. The correlation coefficient between $T_{lowerarm}$ and TSV is the highest, followed by lower leg temperature, and mean skin temperature, with chest temperature having the lowest correlation with thermal sensation. What is more, the change rate of lower arm skin temperature is the largest, followed by the lower leg, and the smallest is the change rate of the chest skin temperature.

(3) When the thermal condition changes, the $T_{lowerarm}$ and T_{ty} increase or decrease logarithmically and reach a relatively stable stage after about 15 min. In a steady-state, the relationships between the $T_{lowerarm}$ and T_{ty} and TSV were linear within a certain range. In an unsteady state, there are strong linear correlations between $\Delta T_{lowerarm}/\Delta t$, $\Delta T_{ty}/\Delta t$, and $\Delta TSV/\Delta t$.

(4) Compared to sunlit spaces, shaded spaces can significantly relieve the outdoor heat stress and improve outdoor thermal comfort. The shaded environments can decrease the average $T_{lowerarm}$ and T_{ty} by about 1.6°C and 0.3°C, respectively.

From a theoretical point of view, these findings related to urban heat stress condition changes can help people to understand the relationship between dynamic thermal sensation and the physiological adjustment process. The practical application of the dynamic model can be stated from the following two aspects. The first is to provide early overheating risk alerts for people undertaking activities outdoors, especially during heatwaves. When a heatwave comes, the rapid rise of skin temperature and core temperature has led to great changes in people's thermal perception. Wearable sensor technology embedded with the dynamic outdoor thermal sensation algorithm can provide early overheating risk alerts for people to protect their health. And the second is to provide the design basis for the establishment of semi-outdoor space. The semi-outdoor space can alleviate the skin temperature and core temperature change rate caused by the change of outdoor thermal stress and prevent excessive changes in heat stress from adversely affecting people's health. This contribution will advance technologies based on the scientific findings to provide alert services to support human health and wellbeing, consequently increasing urban resilience and sustainability.

Acknowledgements

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References

[1]. United Nations, World Urbanization Prospects. (2019).
[2]. Gehl, J., Life between buildings: using public space. Washington, DC: Island Press. (2011).
[3]. Grimmond, C*, et al.* Climate and More Sustainable Cities: Climate Information for Improved Planning and Management of Cities (Producers/Capabilities Perspective). Procedia Environmental Sciences. Vol. 1. (2010). 247-274.
[4]. Edenhofer, O. and K. Seyboth, Intergovernmental Panel on Climate Change (IPCC). (2013).
[5]. Liu, S*, et al.* Dynamic thermal pleasure in outdoor environments - temporal alliesthesia, Science of The Total Environment. 771 (2021) 144910. http://dx.doi.org/10.1016/j.scitotenv.2020.144910.
[6]. Lam, C.K.C*, et al.* Influence of acclimatization and short-term thermal history on outdoor thermal comfort in subtropical South China, Energy and Buildings. 231 (2021). http://dx.doi.org/10.1016/j.enbuild.2020.110541.
[7]. Wei, D*, et al.* Variations in outdoor thermal comfort in an urban park in the hot-summer and cold-winter region of China, Sustainable Cities and Society. 77 (2022). 10.1016/j.scs.2021.103535.
[8]. Chan, E.Y.Y*, et al.* A study of intracity variation of temperature-related mortality and socioeconomic status among the Chinese population in Hong Kong, Journal of Epidemiology and Community Health. 66(4) (2012) 322-327. http://dx.doi.org/10.1136/jech.2008.085167.
[9]. Yang, J., Daily temperature and mortality: a study of distributed lag non-linear effect and effect modification in Guangzhou, Environmental Health. 11(1) (2012) 63-63. http://dx.doi.org/10.1186/1476-069X-11-63.
[10]. Robine, J.-M*, et al.* Death toll exceeded 70,000 in Europe during the summer of 2003, Comptes Rendus Biologies. 331(2) (2008) 171-178. https://doi.org/10.1016/j.crvi.2007.12.001.
[11]. Lowe, D., K.L. Ebi, and B. Forsberg, Heatwave Early Warning Systems and Adaptation Advice to Reduce Human Health Consequences of Heatwaves, Int J Environ Res Public Health. 8(12) (2011) 4623-4648. http://dx.doi.org/10.3390/ijerph8124623.

[12]. Brager, G.S. and R.J. de Dear, Thermal adaptation in the built environment: a literature review, Energy and Buildings. 27(1) (1998) 83-96. https://doi.org/10.1016/S0378-7788(97)00053-4.
[13]. Humphreys, M.A. and J.F. Nicol, Understanding the adaptive approach to thermal comfort, ASHRAE Transactions. 104(1) (1998) 991-1004.
[14]. Hass, A.L. and K.N. Ellis, Motivation for Heat Adaption: How Perception and Exposure Affect Individual Behaviors During Hot Weather in Knoxville, Tennessee, Atmosphere. 10(10) (2019). http://dx.doi.org/10.3390/atmos10100591.
[15]. Huang, Z, *et al.* Outdoor thermal comfort and adaptive behaviors in a university campus in China's hot summer-cold winter climate region, Building and Environment. 165 (2019). http://dx.doi.org/10.1016/j.buildenv.2019.106414.
[16]. Liu, J., R. Yao, and R. McCloy, A method to weight three categories of adaptive thermal comfort, Energy and Buildings. 47 (2012) 312-320. https://doi.org/10.1016/j.enbuild.2011.12.007.
[17]. Stolwijk, J.A., A mathematical model of physiological temperature regulation in man, Nasa Langley (1971).
[18]. Fiala, D., Dynamic Simulation of Human Heat Transfer and Thermal Comfort, in IESD. (1998), De Montfort University.
[19]. Du, C, *et al.* Influence of human thermal adaptation and its development on human thermal responses to warm environments, Building and Environment. 139(JUL.) (2018) 134-145. http://dx.doi.org/10.1016/j.buildenv.2013.12.007.
[20]. ASHARE, Thermal Environmental Conditions for Human Occupancy ASHRAE 55. (2013): American Society Of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.
[21]. ISO, Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Standards Organisation, Geneva. (2006).
[22]. Givoni, B, *et al.* Outdoor comfort research issues, Energy and Buildings. 35(1) (2003) 77-86. 10.1016/S0378-7788(02)00082-8.
[23]. Nikolopoulou, M. and S. Lykoudis, Thermal comfort in outdoor urban spaces: Analysis across different European countries, Building and Environment. 41(11) (2006) 1455-1470. http://dx.doi.org/10.1016/j.buildenv.2005.05.031.
[24]. Spagnolo, J. and R.D. Dear, A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia, Building and Environment. 38(5) (2003) 721-738. http://dx.doi.org/10.1016/S0360-1323(02)00209-3.
[25]. Zhao, L, *et al.* Study on outdoor thermal comfort on a campus in a subtropical urban area in summer, Sustainable Cities and Society. 22 (2016) 164-170. http://dx.doi.org/10.1016/j.scs.2016.02.009.
[26]. Liu, W., Y. Zhang, and Q. Deng, The effects of urban microclimate on outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate, Energy and Buildings. 128 (2016) 190-197. http://dx.doi.org/10.1016/j.enbuild.2016.06.086.
[27]. Lai, D. *et al.* Outdoor space quality: A field study in an urban residential community in central China. 68(7) (2014) 713-720.
[28]. Salata, F, *et al.* Outdoor thermal comfort in the Mediterranean area. A transversal study in Rome, Italy, Building and Environment. 96 (2016) 46-61. http://dx.doi.org/10.1016/j.buildenv.2015.11.023.

[29]. An, L., *et al.* Outdoor thermal comfort during winter in China's cold regions: A comparative study, Science of The Total Environment. 768 (2021) 144464. http://dx.doi.org/10.1016/j.scitotenv.2020.144464.

[30]. Höppe, P., Different aspects of assessing indoor and outdoor thermal comfort, Energy and Buildings. 34(6) (2002) 661-665. http://dx.doi.org/10.1016/S0378-7788(02)00017-8.

[31]. Potchter, O, *et al.* Outdoor human thermal perception in various climates: A comprehensive review of approaches, methods and quantification, Science of The Total Environment. 631-632 (2018) 390-406. http://dx.doi.org/10.1016/j.scitotenv.2018.02.276.

[32]. Liu, K, *et al.* A machine learning approach to predict outdoor thermal comfort using local skin temperatures, Sustainable Cities and Society. 59 (2020). http://dx.doi.org/10.1016/j.scs.2020.102216.

[33]. Deevi, B. and F.A. Chundeli, Quantitative outdoor thermal comfort assessment of street: A case in a warm and humid climate of India, Urban Climate. 34 (2020) 100718. https://doi.org/10.1016/j.uclim.2020.100718.

[34]. Yilmaz, S, *et al.* Analysis of outdoor thermal comfort and air pollution under the nfluence of urban morphology in cold-climate cities: Erzurum/Turkey, Environmental Science Pollution Research (2021) 1-16. http://dx.doi.org/10.1007/s11356-021-14082-3.

[35]. Li, J, *et al.* Exploration of applicability of UTCI and thermally comfortable sun and wind conditions outdoors in a subtropical city of Hong Kong, Sustainable Cities and Society. 52 (2020). http://dx.doi.org/10.1016/j.scs.2019.101793.

[36]. Silva, T.J.V. and S.Q.S. Hirashima, Predicting urban thermal comfort from calibrated UTCI assessment scale - A case study in Belo Horizonte city, southeastern Brazil, Urban Climate. 36 (2021). http://dx.doi.org/10.1016/j.uclim.2020.100652.

[37]. Min, X, *et al.* Outdoor thermal comfort in an urban park during winter in cold regions of China, Sustainable Cities and Society. 43 (2018) 208-220. https://doi.org/10.1016/j.scs.2018.08.034.

[38]. Nagano, K, *et al.* Effects of ambient temperature steps on thermal comfort requirements, International Journal of Biometeorology. 50(1) (2005) 33-39. http://dx.doi.org/10.1007/s00484-005-0265-3.

[39]. Chen, C.-P, *et al.* Effects of temperature steps on human skin physiology and thermal sensation response, Building and Environment. 46(11) (2011) 2387-2397. http://dx.doi.org/10.1016/j.buildenv.2011.05.021.

[40]. Xiong, J, *et al.* Potential indicators for the effect of temperature steps on human health and thermal comfort, Energy and Buildings. 113 (2016) 87-98. http://dx.doi.org/10.1016/j.enbuild.2015.12.031.

[41]. Liu, H, *et al.* The response of human thermal perception and skin temperature to step-change transient thermal environments, Building and Environment. 73(mar.) (2014) 232-238. http://dx.doi.org/10.1016/j.buildenv.2013.12.007.

[42]. Takada, S., S. Matsumoto, and T. Matsushita, Prediction of whole-body thermal sensation in the non-steady state based on skin temperature, Building and Environment. 68 (2013) 123-133. http://dx.doi.org/10.1016/j.buildenv.2013.06.004.

[43]. Fiala, D., K.J. Lomas, and M. Stohrer. First principles modeling of thermal sensation responses in steady-state and transient conditions. in ASHRAE Transactions. 2003.

[44]. Zhang, H, *et al.* Thermal sensation and comfort models for non-uniform and transient environments: Part I: Local sensation of individual body parts, Building and Environment. 45(2) (2010) 380-388. http://dx.doi.org/10.1016/j.buildenv.2009.06.018.

[45]. Lai, D., X. Zhou, and Q. Chen, Modelling dynamic thermal sensation of human subjects in outdoor environments, Energy and Buildings. 149 (2017) 16-25. http://dx.doi.org/10.1016/j.enbuild.2017.05.028.

[46]. Li, H, *et al.* A Survey of Rural Residents' Perception and Response to Health Risks from Hot Weather in Ethnic Minority Areas in Southwest China, International Journal of Environmental Research and Public Health. 16(12) (2019). http://dx.doi.org/10.3390/ijerph16122190.

[47]. Shooshtarian, S., P. Rajagopalan, and A. Sagoo, A comprehensive review of thermal adaptive strategies in outdoor spaces, Sustainable Cities and Society. 41 (2018) 647-665. http://dx.doi.org/10.1016/j.scs.2018.06.005.

[48]. Faul, F, *et al.* Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses, Behavior Research Methods. 41(4) (2009) 1149-60. http://dx.doi.org/10.3758/BRM.41.4.1149.

[49]. Ghahramani, A, *et al.* Infrared thermography of human face for monitoring thermoregulation performance and estimating personal thermal comfort, Building and Environment. 109 (2016) 1-11. https://doi.org/10.1016/j.buildenv.2016.09.005.

[50]. Zhang, H, *et al.* Thermal sensation and comfort models for non-uniform and transient environments, part III: Whole-body sensation and comfort, Building and Environment. 45(2) (2010) 399-410. https://doi.org/10.1016/j.buildenv.2009.06.020.

[51]. Liu, W., Z. Lian, and Q. Deng, Use of mean skin temperature in evaluation of individual thermal comfort for a person in a sleeping posture under steady thermal environment, Indoor and Built Environment. 24(4) (2015) 489-499. http://dx.doi.org/10.1177/1420326X14527975.

[52]. Choi, J.-H. and V. Loftness, Investigation of human body skin temperatures as a bio-signal to indicate overall thermal sensations, Building and Environment. 58 (2012) 258-269. http://dx.doi.org/10.1016/j.buildenv.2012.07.003.

[53]. Standardization, I.O.f., Ergonomics of the Thermal Environment - Instruments for Measuring Physical Quantities. International Standard, ed. I. 7726. (1998): CRC Press, Inc.

[54]. Fang, Z, *et al.* Investigation into sensitivities of factors in outdoor thermal comfort indices, Building and Environment. 128 (2018) 129-142. http://dx.doi.org/10.1016/j.buildenv.2017.11.028.

[55]. Yao, Y, *et al.* Experimental Study on Skin Temperature and Thermal Comfort of the Human Body in a Recumbent Posture under Uniform Thermal Environments, Indoor and Built Environment. 16(6) (2016) 505-518. http://dx.doi.org/10.1177/1420326x07084291.

[56]. Lu, C., Study on the relationship between indoor thermal environment and human thermal comfort and health in hot summer and cold winter areas. (2006), Chongqing University.

[57]. Liu, W, *et al.* Evaluation of calculation methods of mean skin temperature for use in thermal comfort study, Building and Environment. 46(2) (2011) 478-488. http://dx.doi.org/10.1016/j.buildenv.2010.08.011.

[58]. Åstrand, P.O., Rodahl, K., Dahl, H.A., Strømme, S.B., Textbook of Work Physiology:Physiological Bases of Exercise, fourth ed. Human Kinetics, Champaign. (2003).

[59]. Lee, J.-Y, *et al.* Validity of Infrared Tympanic Temperature for the Evaluation of Heat Strain While Wearing Impermeable Protective Clothing in Hot Environments, Industrial Health. 49(6) (2011) 714-725. http://dx.doi.org/10.2486/indhealth.MS1291.

[60]. Woodman, E.A., S.M. Parry, and L. Simms, Sources of unrealiability in oral temperatures, Nursing Research. 16(3) (1967) 276-279. http://dx.doi.org/10.1097/00006199-196701630-00014.

[61]. Guozhong, Z., Study on physioloical responses of relaive population in hot and numid environments. (2015), Tianjin University.

[62]. Sund-Levander M , F.C., Wahren L K Normal oral rectal tympanic and axillary body temperature in adult men and women: a systematic literature review, Scandinavian Journal of Caring Sciences 16(2) (2010) 122-128. http://dx.doi.org/10.1046/j.1471-6712.2002.00069.x.

[63]. Ko, Y*, et al.* Auditory canal temperature measurement using a wearable device during sleep: Comparisons with rectal temperatures at 6, 10, and 14cm depths, Journal of Thermal Biology. 85 (2019) 102410. http://dx.doi.org/10.1016/j.jtherbio.2019.102410.

[64]. Greenleaf, J.E. and B.L. Castle, External auditory canal temperature as an estimate of core temperature, Journal of Applied Physiology. 32(2) (1972) 194.

[65]. Lee, J.Y*, et al.* Validity of infrared tympanic temperature for the evaluation of heat strain while wearing impermeable protective clothing in hot environments, Industrial Health. 49(6) (2011) 714-725. http://dx.doi.org/10.2486/indhealth.MS1291.

[66]. Mahmoud, S*, et al.* Accuracy and Precision of Tympanic Temperature in the Reflection of Core Temperature, Iran Journal of Nursing (2006).

[67]. Cohen, P., O. Potchter, and A. Matzarakis, Human thermal perception of Coastal Mediterranean outdoor urban environments, Applied Geography. 37 (2013) 1-10. http://dx.doi.org/10.1016/j.apgeog.2012.11.001.

[68]. Kuwabara, K*, et al.* Effective radiant temperature including solar radiation, Elsevier Ergonomics Book. 3(05) (2005) 257-262. http://dx.doi.org/10.1016/S1572-347X(05)80042-4.

[69]. Yahia, *et al.*, Evaluating the behaviour of different thermal indices by investigating;various outdoor urban environments in the hot dry city of Damascus,Syria, International Journal of Biometeorology. 57(4) (2013) 615-630. http://dx.doi.org/10.1007/s00484-012-0589-8.

[70]. Yin, S*, et al.* Comparing cooling efficiency of shading strategies for pedestrian thermal comfort in street canyons of traditional shophouse neighbourhoods in Guangzhou, China, Urban Climate. 43 (2022) 101165. https://doi.org/10.1016/j.uclim.2022.101165.

[71]. Ji, W*, et al.* A new method to study human metabolic rate changes and thermal comfort in physical exercise by CO2 measurement in an airtight chamber, Energy and Buildings. 177 (2018) 402-412. 10.1016/j.enbuild.2018.08.018.

[72]. Wang, Z*, et al.* Human thermal physiological and psychological responses under different heating environments, Journal of Thermal Biology. 52 (2015) 177-86. http://dx.doi.org/10.1016/j.jtherbio.2015.06.008.

[73]. Choi, J.-H. and D. Yeom, Study of data-driven thermal sensation prediction model as a function of local body skin temperatures in a built environment, Building and Environment. 121 (2017) 130-147. http://dx.doi.org/10.1016/j.buildenv.2017.05.004.

[74]. Sharmin, T., S. Kabir, and M.M. Rahaman, A Study of Thermal Comfort in Outdoor Urban Spaces in respect to Increasing Building Height in Dhaka, The AIUB Journal of Science and Engineering 11(01) (2012).

[75]. Pantavou, K*, et al.* Outdoor thermal sensation of pedestrians in a Mediterranean climate and a comparison with UTCI, Building and Environment. 66(4) (2013) 82-95. http://dx.doi.org/10.1016/j.buildenv.2013.02.014.

[76]. Park, S., S.E. Tuller, and M. Jo, Application of Universal Thermal Climate Index (UTCI) for microclimatic analysis in urban thermal environments, Landscape and Urban Planning. 125(2) (2014) 146-155. http://dx.doi.org/10.1016/j.landurbplan.2014.02.014.

[77]. Höppe, P., The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment, International Journal of Biometeorology. 43(2) (1999) 71-75.

[78]. Wang, D*, et al.* Observations of upper-extremity skin temperature and corresponding overall-body thermal sensations and comfort, Building and Environment. 42(12) (2007) 3933-3943. http://dx.doi.org/10.1016/j.buildenv.2006.06.035.

[79]. Hensel, H., Cutaneous thermoreceptors, Thermoreception and Temperature Regulation (1981) 33-63.

[80]. Dear, R., J.W. Ring, and P.O. Fanger, T hermal sensations resulting from sudden ambient temperature changes, Indoor air. 3(3) (1993) 181-192.

[81]. Ring, J.W. and R. de Dear, Temperature Transients: A Model for Heat Diffusion through the Skin, Thermoreceptor Response and Thermal Sensation, Indoor Air. 1(4) (1991) 448-456. http://dx.doi.org/10.1111/j.1600-0668.1991.00009.x.

[82]. Chenqiu Du, B.L., Characteristics and evaluation of human thermal responses with time unber temperature step change condition. , HV&AC. 49(4) (2019) 19-26.

[83]. Fußeder, M., R. Wüchner, and K.-U. Bletzinger, Towards a computational engineering tool for structural sensitivity analysis based on the method of influence functions, Engineering Structures. 265 (2022) 114402. https://doi.org/10.1016/j.engstruct.2022.114402.

[84]. Gou, S*, et al.* Passive design optimization of newly-built residential buildings in Shanghai for improving indoor thermal comfort while reducing building energy demand, Energy and Buildings. 169 (2018) 484-506. https://doi.org/10.1016/j.enbuild.2017.09.095.

[85]. Lin, K*, et al.* Dimensionality reduction for surrogate model construction for global sensitivity analysis: Comparison between active subspace and local sensitivity analysis, Combustion and Flame. 232 (2021) 111501. https://doi.org/10.1016/j.combustflame.2021.111501.

[86]. Cao, X*, et al.* Energy-quota-based integrated solutions for heating and cooling of residential buildings in the Hot Summer and Cold Winter zone in China, Energy and Buildings. 236 (2021) 110767. https://doi.org/10.1016/j.enbuild.2021.110767.

[87]. Chen, L. and E. Ng, Outdoor thermal comfort and outdoor activities: A review of research in the past decade, Cities. 29(2) (2012) 118-125. http://dx.doi.org/10.1016/j.cities.2011.08.006.

[88]. Kruger, E.L. and P. Drach, Identifying potential effects from anthropometric variables on outdoor thermal comfort, Building and Environment. 117 (2017) 230-237. http://dx.doi.org/10.1016/j.buildenv.2017.03.020.

[89]. Qu, S., Z. Wang, and W. Liu, Clothing adjustment in outdoor environment: A new clothing model based on temperature change, Building and Environment. 206 (2021) 108395. https://doi.org/10.1016/j.buildenv.2021.108395.

[90]. Du, C*, et al.* Moisture in clothing and its transient influence on human thermal responses through clothing microenvironment in cold environments in winter, Building and Environment. 150 (2019) 1-12. https://doi.org/10.1016/j.buildenv.2018.12.066.