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ORIGINAL PAPER

A comparative analysis of human thermal conditions in outdoor urban spaces in the summer season in Singapore and Changsha, China

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Abstract This paper presents the comparative analysis between the findings from two field surveys of human thermal conditions in outdoor urban spaces during the summer season. The first survey was carried out from August 2010 to May 2011 in Singapore and the second survey was carried out from June 2010 to August 2010 in Changsha, China. The physiologically equivalent temperature (PET) was utilized as the thermal index to assess the thermal conditions. Differences were found between the two city respondents in terms of thermal sensation, humidity sensation, and wind speed sensation. No big difference was found between the two city respondents regarding the sun sensation. The two city respondents had similar neutral PET of 28.1 °C for Singapore and 27.9 °C for Changsha, respectively. However, Singapore respondents were more sensitive to PET change than Changsha respondents and the acceptable PET range for Changsha respondents was wider than that for Singapore respondents. Besides, the two city respondents had different thermal expectations with the preferred PET of 25.2 °C and 22.1 °C for Singapore and Changsha, respectively. The results also reveal that Changsha respondents were more tolerant than Singapore respondents under hot conditions. Finally, two regression models were proposed for Singapore and Changsha to predict the human thermal sensation in a given outdoor thermal environment.

Keywords Comparative analysis · Human thermal conditions · Outdoor urban spaces · Physiologically equivalent temperature · Thermal expectations

Introduction

Over the years, many field studies on thermal comfort have been conducted in different outdoor spaces and in different seasons across different geographical/climatic zones (Höppe and Seidl 1991; Nikolopoulou et al. 2001; Spagnolo and de Dear 2003; Ahmed 2003; Givoni et al. 2003; Thorsson et al. 2004; Nikolopoulou and Lykoudis 2006, 2007; Oliveira and Andrade 2007; Hwang and Lin 2007; Lin and Matzarakis 2008; Lin et al. 2010; Hwang et al. 2010; Ng and Cheng 2011; Kántor and Unger 2011; Lin et al. 2012). These studies have provided valuable information on the understanding of the effects of outdoor climatic conditions and thermal adaptation factors (Hwang et al. 2007; Lin et al. 2011) on people's thermal sensation as well as the use of outdoor spaces (Lin 2009). However, the quantification of outdoor thermal comfort is a relatively new area of inquiry compared with indoor thermal comfort. Empirical data from field surveys on the subjective human parameter in the outdoor context is still needed, as this would provide a broader perspective from which to view comfort in urban spaces (Nikolopoulou and Lykoudis 2006). By comparing outdoor comfort studies conducted in different seasons or different climatic zones, it would be possible to evaluate the effect of changes in the prevailing climatic conditions on the temperature range within which people feel comfortable outdoors (Givoni et al. 2003), and to understand how people

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would adapt to their local climates. This paper presents results from two comprehensive field studies on outdoor human thermal conditions which were carried out separately in Singapore and Changsha, China. The main aim was to compare thermal responses and thermal adaptation of people in outdoor urban spaces in Singapore and Changsha, China. Since Singapore is a country with summer all year round, the field study in Changsha was carried out in the summer season to ensure the comparability of human thermal conditions in Changsha and Singapore.

According to adaptive theory (Brager and de Dear 1998; Humphreys and Nicol 1998), individuals can adapt themselves to outdoor thermal conditions and the temperatures customary for comfort vary geographically and seasonally with the climate (Humphreys et al. 2007). Knez and Thorsson (2006) found that people living in different cultures with different environmental attitudes would psychologically evaluate a Swedish and a Japanese square differently despite similar thermal conditions. Zhang et al. (2010) also indicated that thermal sensitivity may be relevant to the annual variation of outdoor climate and people can develop various human-environment relationships through thermal adaptation to local climate. Based on the above adaptive theory, we hypothesize that occupants in Singapore and Changsha should be both well adapted to their local climates, and occupants in Singapore and Changsha should have different thermal comfort requirements for the outdoor urban spaces because of the different variation of outdoor climate in Singapore and Changsha in summer. This hypothesis needs to be tested by examining whether respondents have different thermal responses in terms of thermal neutrality, thermal sensitivity, thermal preference and thermal acceptability.

Additionally, in order to evaluate the importance of modifying the outdoor climate in a particular direction by specific design details, it would be helpful if the designer would have some means for ‘predicting’ the effect of a particular change in a climatic element on the comfort of persons staying outdoors (Givoni et al. 2003). Thus, this study also proposed two regression models for Singapore and Changsha to predict thermal sensation of people as a function of outdoor thermal environmental parameters. The regression models could be applied by urban designers to evaluate the thermal sensation of users in a given outdoor environment and thus determine whether the outdoor thermal conditions are comfortable or not.

Materials and methods

Study areas

This study includes two field surveys of outdoor thermal conditions in two cities in different parts of the world. The first survey was conducted in 13 outdoor urban spaces in Singapore from August 2010 to May 2011. The second survey was performed in 17 outdoor urban spaces in Changsha from June 2010 to August 2010. The outdoor spaces studied included parks, squares, streets and university campuses in the field surveys. The site selection process aimed to capture a wide range of environmental and microclimatic conditions in both cities. The areas selected for the study were typical resting places in outdoor urban spaces. The descriptions of each study area are presented in Tables 1 and 2. Respondents with age younger than 20 or older than 60 were not included in the analysis. A total of 4,072 valid questionnaires were collected during the two surveys. The distribution of sample data is presented in Table 3.

Table 1 Descriptions of each study area in Singapore

Study area		Descriptions
Park	East Coast Park	In the east part of the city, along the sea, with trees and grass
	West Coast Park	In the west part of the city, along the sea, with trees and grass
	Chinese Garden	In the west part of the city, with tress, grass, and several small lakes
	Botanic Garden	In the centre of the city, with trees, grass, and several small lakes
	Ang Mo Kio Town Garden	In the north part of the city, with trees and grass
	Yishun Park	In the north part of the city, with trees and grass
Square	City Hall Square	In the downtown area, commercial centre, with trees, grass and shading structures
	Vivo City Square	In the south part of the city, near the sea, with shading structures but no trees
Street or road	Orchard Road	In the downtown area, commercial centre, with trees
	Chinatown Food Street	In the south part of the city, dining area, with shading structures but no trees
University campus	National University of Singapore	In the southwest part of the city, with trees and grass
	Nanyang Technological University	In the west part of the city, with trees and grass
Others	Clark Quay	Along Singapore river walk, recreation and dining area, with trees and shading structures

Table 2 Descriptions of each study area in Changsha

Study area		Descriptions
Park	Nanjiao Park	In the south part of the city, covered with trees
	Martyr memorial park	In the north part of the city, with tress and a large lake
	Moon Lake Park	In the northeast part of the city, with trees and grass and several big lakes
	Orange Park	In the west part of the city, along Xiangjiang River, covered with trees and grass
	Botanic Garden	In the south part of the city, covered with trees
	Yuelushan National Park	In the west part of the city, at the foot of Yuelu mountain, with trees and grass
Square	Dongfanghong Square	In the west part of the city, at the foot of Yuelu mountain, with trees
	One best Plaza	In the west part of city, commercial centre, with no trees, no shading structures
	Windows of the World	In the north east of the city, with no trees, no shading structures
	Huangxing Square	In the downtown area, with no trees, no shading structures
Street or road	South Huangxing Ambulation Street	In the downtown area, commercial centre, with trees and shading structures
	Xiaoxiang Road	In the west part of the city, along the Xiangjiang River, comprising a paved sidewalk, with few trees
	Yanjiang Road	In the east part of the city, comprising a paved sidewalk, with trees
University campus	Hunan University	In the west part of the city, with trees, and terrible traffic in the campus
	Hunan Normal University	In the west part of the city, with trees, and terrible traffic in the campus
	Central South University	In the southwest part of the city, with trees and several small lakes
	Changsha University of Science and Technology	In the city centre, with trees

Climate background

Singapore is situated between 103° 36′ E and 104° 25′ E longitude and 1° 09′ N and 1° 29′ N latitude. According to Köppen-Geiger climate classification, Singapore's climate is classified as tropical rainforest climate. It has high and uniform temperature and high humidity all year round. The diurnal temperature variations are small with the range for minimum and maximum temperatures of 24 °C to 26 °C and 31 °C to 33 °C, respectively. The mean annual relative humidity is 84 %. There are 2064 sunshine hours annually and approximately 5.7 sunshine hours for each day. On an average day, cumulus clouds start to develop in the mid-morning, increasing to about 3–4 oktas by midday with bases of around 0.6 km and tops from 2.5 to 3.5 km. During the afternoon and early evening, these cumulus clouds may develop into cumulonimbus clouds with tops reaching between 9 and 12 km. The clouds diminish and begin to flatten into stratiform layers by dusk and slowly disperse during the night (Fong et al. 2012). The average and maximum hourly global radiation is 189 Wh/W^2 and 882 Wh/W^2, respectively, in Singapore.

Table 3 Sampling distribution of 4,072 questionnaires

Characteristic	Singapore	Changsha
Sample size	2020	2052
Gender		
Male	1005	993
Female	1015	1059
Age (years)		
Mean	30.3	25.9
SD	14.1	9.2
Minimum	20	20
Maximum	60	60
Years living in local cities		
Mean	7.3	10.3
SD	14.5	15.3
Minimum	0.5	0.5
Maximum	46	50

Changsha is located in south central China at a longitude between 111° 53′ E and 114° 5′ E and latitude between 27° 51′ N and 28° 40′ N. According to Köppen-Geiger climate classification, Changsha is classified as a humid subtropical climate. It has four distinct seasons with a long summer and winter and short spring and autumn. The summer season in Changsha (from June to August) is characterized by high air temperature, high humidity and high solar radiation. Under the control of subtropical high air pressure, high temperatures hold up through the whole summer. The average minimum temperature is 22 °C and average maximum temperature is 36 °C in Changsha in summer. The relative humidity frequently exceeds 75 % in summer. The average sunshine hours is 7.4 per day in summer. The average and maximum hourly global radiation is 185 Wh/W^2 and 1294 Wh/W^2, respectively, in Changsha in summer.

It can be seen that Singapore and Changsha both experience hot and humid climatic conditions during the study period. However, the variation of outdoor climate in Changsha (temperature range of 22–36 °C) in summer is larger than that in Singapore (temperature range of 24–33 °C). This study hypothesizes that occupants in Singapore and Changsha have different thermal comfort requirements for the outdoor urban spaces because of the different variation of outdoor climate in Singapore and Changsha in summer.

Data collection

Data collection was basically divided into environmental and human monitoring (questionnaire), which were carried out simultaneously. Environmental monitoring recorded the microclimatic conditions in the immediate surroundings of the respondents. The microclimatic parameters considered in the analysis are air temperature (Ta), globe temperature (Tg), relative humidity (RH), vapour pressure (VP), wind speed (v) and global radiation (GR).

During the Singapore survey, air temperature, relative humidity and wind speed were measured by Testo 445, a system for flexible measurement of different measurement data. Globe temperature was measured using a 38-mm diameter black globe thermometer. Global radiation was tracked by a CM6B Pyranometer, which is a combination of direct and diffuse solar radiation and the radiation emitted from the surroundings. The instrument used for the field survey in Changsha was Swema 3000. Three probes were equipped with Swema 3000, among which the Swa03 probe measured wind speed and air temperature, the Hygroclip S probe measured relative humidity and air temperature and the SWAT probe measured globe temperature. Global radiation in Changsha was measured by the AM-20P Pyranometer. The accuracy of the all the instruments conformed to ISO 7726 (ISO 1985). The measurement height was 1.1 m, corresponding to the average height of the centre of gravity for adults (Mayer and Höppe 1987).

Human monitoring addressed the subjective thermal responses including the respondents' thermal sensation, thermal preference, thermal acceptability, humidity sensation, wind speed sensation, sun sensation, and thermal adaptation as well as respondents' demographic background, clothing and activity level. The various scales used for the subjective assessment in the survey are listed in Table 4. Besides, an observation sheet was used to record the weather conditions, location, date and time, environmental parameters, respondents' clothing and activity for double checking and other information which may influence the results. The scope of the questionnaire was based on several preceding studies with special reference to the one used in the RUROS project in Europe (Nikolopoulou and Lykoudis 2006) and the one used in an indoor thermal comfort study in China (Yang and Zhang 2008) as well as the ASHRAE standard questionnaire for indoor thermal comfort study (ASHRAE 2004).

Metabolic rate and clothing insulation were estimated in accordance with ASHRAE standard 55–2004 (ASHRAE 2004). The standard provided a checklist of typical activities and their corresponding metabolic rates. As only respondents who were sitting and standing participated in the survey, the metabolic rate was assumed to be 1.2 met and 1.4 met for sitting and standing respondents, respectively (1 met=58.15 W/m^2). The typical attire of people in Singapore and Changsha in the summer season are the same with short T-shirt and short pants or short skirt. The average clothing value was found to be 0.30 clo (1 clo=0.155 °C m^2/W) for both city respondents.

Outdoor thermal comfort indices

Several integrative thermal indices derived from the human energy balance, e.g., predicted mean vote (PMV) (Fanger 1970), perceived temperature (PT) (Jendritzky et al. 2000), outdoor standard effective temperature (OUT_SET*) (Spagnolo and de Dear 2003), physiologically equivalent temperature (PET) (VDI 1998; Höppe 1999; Matzarakis et al. 1999), universal thermal climate index (UTCI) (Bröde et al. 2012), have been developed to quantify human thermal comfort. Among these various indices, PET has been widely used for outdoor thermal assessment (Knez and Thorsson 2006; Lin and Matzarakis 2008; Lin 2009; Lin et al. 2010; Ng and Cheng 2011; Cohen et al. 2012), and it has been adopted by the German guidelines for urban and regional planners (VDI

Table 4 Scales used for subjective assessment in the survey

ASHRAE scale	Thermal preference	Humidity sensation	Humidity preference	Wind sensation	Wind preference	Sun sensation	Sun preference	Acceptability
−3 cold	Warmer	−2 too dry	Less humid	−2 stale	Less	−2 too weak	Weaker	Acceptable
−2 cool	No change	−1 dry	No change	−1 little wind	No change	−1 little weak	No change	Unacceptable
−1 slightly cool	Cooler	0 ok	More humid	0 ok	Greater	0 ok	Stronger	
0 neutral		+1 humid		+1 windy		+1 little strong		
+1slightly warm		+2 very humid		+2 too much wind		+2 Too strong		
+2 warm								
+3 hot								

1998). Therefore, PET was applied in this study as the thermal comfort index in evaluating outdoor thermal comfort.

RayMan model

PET can be calculated using the RayMan model (Matzarakis et al. 2007; Matzarakis et al. 2010). PET can be easily estimated by air temperature (Ta), relative humidity (RH) or vapour pressure (VP), wind speed (*v*), mean radiant temperature (Tmrt), human clothing and activity in the model (Lin et al. 2010). If more information is offered, the mean radiant temperature can be also estimated by global radiation, cloud cover, fisheye photographs, albedo, the Bowen ratio of ground surface and the Linke turbidity to include the shading effect while calculating short- and long-wave radiation fluxes (Hwang et al. 2011).

In this study the mean radiant temperature (Tmrt) was estimated using the globe temperature method (Thorsson et al. 2007). Thorsson et al. (2007) compared different methods for estimating outdoor mean radiant temperature and found that the difference was relatively small between the globe thermometer method and the more complicated method based on integral radiation measurements and angular factor. A 38-mm diameter black-coloured globe thermometer was used in this study. It has been pointed out that the use of a black-coloured globe tends to overestimate the influence of short-wave radiation (Olesen et al. 1989). Lowering the albedo of the globe slightly could improve the accuracy and thus a 38-mm flat grey-coloured globe thermometer was recommended by Thorsson et al. (2007). Due to the limited resources, a black-coloured instead of grey-coloured globe thermometer was used in this study. The mean radiant temperature can also be estimated by the RayMan model. This paper gives a comparison of mean radiant temperature calculated by the globe temperature method and the RayMan model.

If running PET with RayMan, the model assumes 0.9 clo for clothing level and 80 W for activity level. However, this does not essentially restrict its applicability, as the variation of clothing and activity does not lead to significantly different PET values if varied equally outdoors and in the reference indoor climate (Höppe 1999). Besides, the clothing and activity values in this study do not vary significantly between the respondents, and the small differences of clothing and activity values will not affect PET significantly.

Data processing

For the purpose of comparing the thermal responses of Singapore and Changsha respondents with regard to the outdoor thermal environment, descriptive analysis and independent t-test was applied using SPSS software to interpret and analyse some of the survey results. The independent t-test is an inferential statistical test that determines whether there is a statistically significant difference between the means in two unrelated groups (Dowdy et al. 2004). Thus, this statistical test reveals if the two city respondents have significantly different thermal responses on the outdoor thermal environment.

Results and discussion

Statistical summary of meteorological conditions

Table 5 gives the statistical summary of meteorological conditions for both Singapore and Changsha. It is apparent that air temperature was quite high in both cities, with a mean air temperature of 30.9 °C in Singapore and 32.3 °C in Changsha. Relative humidity was also high in both cities. Wind speed was relatively low with a mean of 1.0 m/s in Singapore and 0.9 m/s in Changsha. The global radiation was not very high in both cities as most of the surveys were conducted in shaded areas and some of the surveys were conducted during evening. PET was high in both cities with an average value of 32.0 °C in Singapore and 33.1 °C in Changsha.

It can be seen that the outdoor climate conditions in both cities were similar with hot and humid conditions. However,

Table 5 Statistical summary of meteorological conditions

Measurement	Singapore				Changsha			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Air temperature (°C)	30.9	1.6	26.3	36.0	32.3	2.7	26.4	38.4
Globe temperature (°C)	32.2	2.3	26.6	39.2	32.9	3.0	26.5	40.4
Relative humidity (%)	69.6	7.9	47.8	90.8	64.8	11.0	40.0	90.3
Vapour pressure (hPa)	31.0	2.2	23.7	37.4	31.0	2.6	22.8	37.5
Wind speed (m/s)	1.0	0.7	0.1	4.5	0.9	0.6	0.1	3.2
Global radiation (W/m^2)	201.9	114.4	0	738.0	174.5	99.0	0	714.0
Mean radiant temperature (°C)	34.7	4.3	26.0	64.3	34.1	4.9	26.3	64.9
PET (°C)	32.0	2.9	24.0	44.7	33.1	4.1	24.0	50.5

some differences between outdoor climate variables in the two cities can be observed. Outdoor air temperature and PET in Changsha were higher than those in Singapore, indicating that the climatic condition in Changsha was hotter than that in Singapore. Relative humidity, wind speed and global radiation were all higher in Singapore than those in Changsha.

Relationship between measured mean radiant temperature and modelled mean radiant temperature by RayMan

Figure 1 shows the relationship between the measured Tmrt by globe temperature and modelled Tmrt by RayMan for both Singapore and Changsha. The measured and modeled Tmrt were well correlated ($R^2=0.924$ for Singapore and $R^2=0.905$ for Changsha) and the regression was statistically significant at the 95 % level. The result indicates that RayMan can accurately predict Tmrt in both Singapore and Changsha.

Relationship between measured mean radiant temperature and PET

Figure 2 shows the relationship between measured Tmrt and PET for both Singapore and Changsha. PET was well correlated with measured Tmrt ($R^2=0.743$ for Singapore and $R^2=0.796$ for Changsha) and the regression was statistically significant at the 95 % level. It has been pointed out by Mayer et al. (2008) that among the meteorological variables necessary to calculate PET, the strongest influence on PET was exerted by Tmrt. The result in this study is in agreement with the above point.

Subjective responses

Perception of air humidity

Figure 3 presents the mean humidity sensation votes at different vapour pressure range for both Singapore and Changsha. It shows that with the same vapour pressure, the mean humidity sensation vote in Singapore was higher than that in Changsha, indicating that respondents generally felt more humid in Singapore than in Changsha. T-test also shows that the difference between the two city respondents was statistically significant ($t(24)=-3.011$, $P=0.006<0.05$).

Perception of wind speed

Since the perception of wind is closely related to air temperature, simple linear regression analysis was performed to find out the relationship between the mean wind speed sensation votes (MWSV) and outdoor wind speed (v) at different PET limits.

The regression equations for both cities are listed in Table 6. The optimum wind speed that respondents felt fine at each PET range was derived by solving the equations for a mean sensation vote of zero. From the p-values presented in the table, it can be seen that the correlation between MWSV and outdoor wind speed was significant for all the equations ($p<0.001$).

In Singapore, in the PET ranges of 24–28 °C, 28–32 °C, 32–36 °C and >36 °C, the optimum wind speeds required by respondents were 1.2 m/s, 1.5 m/s, 2.1 m/s and 2.3 m/s, respectively. In Changsha, in the PET ranges of 24–28 °C, 28–32 °C, 32–36 °C and >36 °C, the optimum wind speeds required by respondents were 1.3 m/s, 1.7 m/s, 2.0 m/s and 2.3 m/s, respectively. The results in both cities suggest that the higher the PET, the higher the wind speed required by respondents in order to feel comfortable. However, it should be noted that when the air temperature gets closer to body temperature (37 °C), heat transfer from the human body to the environment is reduced, and thus even the increase of air movement (speeding up evaporation) would not make people feel comfortable under extremely high temperature and high humidity in a hot and humid climate.

The gradient of the regression model in Table 6 can be used to evaluate the wind speed sensitivity of the respondents to outdoor wind speed. It can be observed that there was a decreasing tendency of the regression slope from the

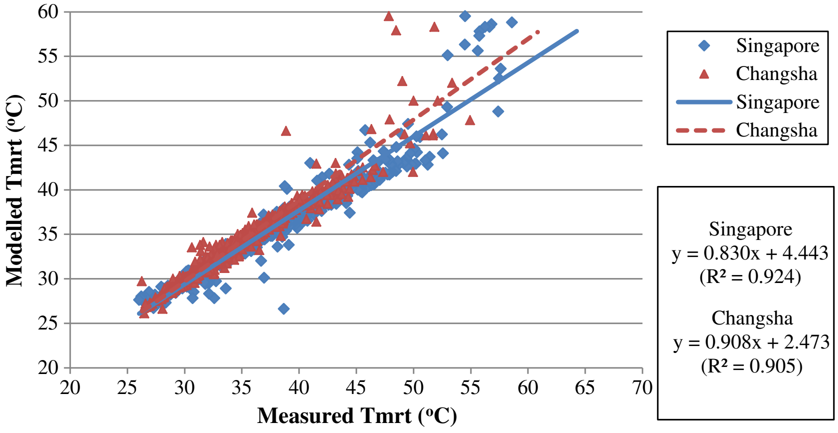


Fig. 1 Relationship between measured mean radiant temperature and modelled mean radiant temperature by RayMan

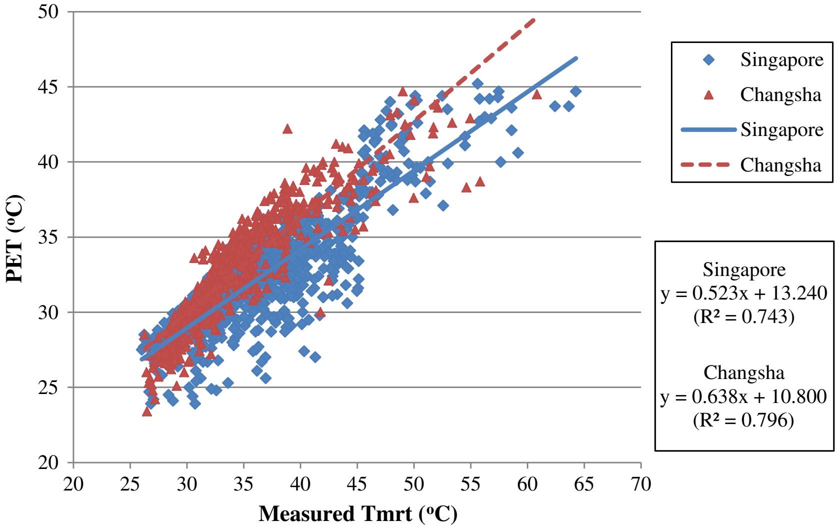


Fig. 2 Relationship between measured mean radiant temperature and physiologically equivalent temperature (PET)

temperature range of 24–28 °C to >36 °C, which varied from 0.729 to 0.468 for Singapore and 0.885 to 0.457 for Changsha, suggesting that the respondents became less sensitive to the wind speed with increasing PET.

By comparing the optimum wind speed respondents required in Singapore and Changsha, it can also be seen that the optimum wind speeds at each PET range were similar in Singapore and Changsha, with a difference of less than 0.2 m/s. However, Changsha respondents were more sensitive to the wind speed than the Singapore respondents.

Perception of sun

Figure 4 shows the mean sun sensation votes at different global radiation range for both Singapore and Changsha. At lower global radiation (<500 W/m^2), not much difference was found between the two cities regarding sun sensation. At higher global radiation (>500 W/m^2), Singapore respondents felt that the sun was much stronger than Changsha respondents. However, this difference could be due to the relatively small sample size at the high global radiation level. T-test also shows that the difference between the two city respondents was not statistically significant (t(28)=−0.378, P=0.708>0.05).

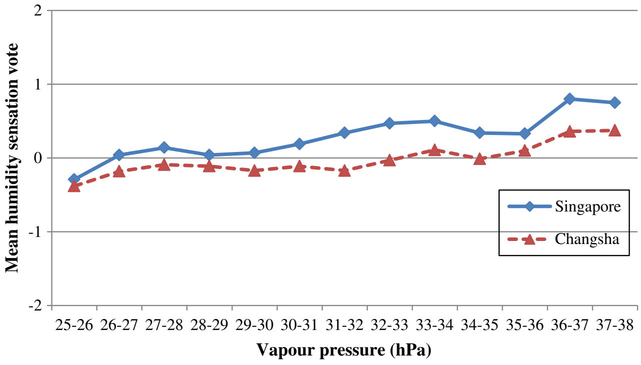


Fig. 3 Humidity sensation and relative humidity

Neutral PET

Neutral PET was usually determined by analyzing the relationship between thermal sensation votes (TSV) and PET. Figure 5 presents the regression of mean thermal sensation votes (MTSV) and PET for both cities. Equations (1) and (2) show the linear regression for Singapore and Changsha, respectively.

$$\mathrm{MTSV} = 0.234\mathrm{PET} - 6.566\mathrm{R}^2 = 0.953 \tag{1}$$

$$\mathrm{MTSV} = 0.168\mathrm{PET} - 4.686\mathrm{R}^2 = 0.896 \tag{2}$$

For both cities, the mean thermal sensation votes correlated strongly with PET that can explain about 90 % of the variability of the thermal sensation votes (R^2=0.953 in Singapore and R^2=0.896 in Changsha). The neutral PET was derived by solving the equations for a mean sensation vote of zero, and the neutral PET was 28.1 °C for Singapore and 27.9 °C for Changsha. The high neutral temperatures in both cities indicate that respondents have well adapted to the hot conditions.

It can be seen in Fig. 5 that under warmer/hotter conditions (PET>30 °C), Singapore respondents perceived the thermal environment as warmer than Changsha respondents, suggesting that Changsha respondents may be more tolerant than Singapore respondents under hot conditions. Further analysis with t-test revealed that under hot conditions (PET>30 °C) Singapore respondents felt significantly warmer than Changsha respondents (t(2860.221)=−2.197, p=0.028<0.05). However, the difference between the two city respondents under relatively cooler conditions (PET<30 °C) was not statistically significant (t(1033.444)=1.711, p=0.087>0.05).

Table 6 Regression of wind speed sensation and outdoor wind speed

Location	PET	Regression equation	R^2	F-test	P-value	Optimum wind speed
Singapore	24–28 °C	$MWSV = 0.729v - 0.883$	0.602	39.258	$P<0.001$	1.2 m/s
	28–32 °C	$MWSV = 0.582v - 0.890$	0.716	65.700	$P<0.001$	1.5 m/s
	32–36 °C	$MWSV = 0.543v - 1.117$	0.557	28.892	$P<0.001$	2.1 m/s
	>36 °C	$MWSV = 0.468v - .070$	0.648	36.835	$P<0.001$	2.3 m/s
Changsha	24–28 °C	$MWSV = 0.885v - 1.106$	0.711	36.946	$P<0.001$	1.3 m/s
	28–32 °C	$MWSV = 0.639v - 1.107$	0.852	103.994	$P<0.001$	1.7 m/s
	32–36 °C	$MWSV = 0.533v - 1.066$	0.726	60.920	$P<0.001$	2.0 m/s
	>36 °C	$MWSV = 0.457v - 1.043$	0.631	46.263	$P<0.001$	2.3 m/s

PET physiologically equivalent temperature

The result confirms that thermal expectation and seasonal adjustment which vary according to race, culture and adaptation, obviously do not lead to different evaluations of slightly warm or cool conditions, but rather to different interpretations of hot or cold environments (Wyon 1993).

The regression slope in Singapore was 0.234/°C, which was higher than that in Changsha of 0.168/°C. As the gradient of the regression models measures the thermal sensitivity, this means that respondents in Singapore were more sensitive to the variations of the PET than respondents in Changsha. On average, mean thermal sensations changed one unit every 4.3 °C of PET in Singapore, whereas in Changsha, 6.0 °C were needed to shift mean thermal sensation jump by one unit.

The key reason that Singapore respondents were more sensitive to temperature variations than Changsha respondents is that Singapore respondents experienced a narrower PET range (24.0–41.1 °C) than Changsha respondents (24.0–50.5 °C). According to Humphreys et al. (2007), there can be a tendency (range effect) for respondents to adjust their voting to accommodate the range of the subjective scale to the range of conditions they experience, suggesting that people accustomed to a wide range of room temperature might be less sensitive to change than those accustomed to smaller variations.

Acceptable PET range

Figure 6 shows the relationship between percentage of unacceptability and PET for both Singapore and Changsha. In line with the method used by Lin and Matzarakis (2008) in Taiwan, the 88 % acceptability limits were chosen for “neutral” thermal sensation in order to determine the acceptable temperature range based on PET. The 88 % acceptability limits are the intersections of the fitted curve and the 12 % unacceptability line, which were 18.7–30.3 °C and 18.6–31.2 °C for Singapore and Changsha, respectively. It can be seen that the acceptable PET for Changsha was slightly wider than that for Singapore.

Since the lowest PET was 24 °C in this study, PET ranges of 24–30 °C and 24–31 °C were considered as “neutral” in Singapore and Changsha, respectively. According to Lin and Matzarakis (2008), the PET ranges of “slightly warm”, “warm” and “hot” thermal sensation are obtained through a 4 °C increase of the PET range of “neutral”; and “slightly cool” is obtained through a 4 °C decrease of the “neutral” range. The ranges of “cool”, “cold” and “very cold” thermal sensation are not assigned because cool/cold discomfort rarely occurred in either Singapore or Changsha during the summer.

Table 7 shows the thermal sensations and PET classes for Singapore and Changsha. The results are compared with the classifications in Taiwan (Lin and Matzarakis 2008) and Western/Middle Europe (Matzarakis and Mayer 1996). It shows that the PET ranges for each thermal sensation scale in Singapore are the same as that in Taiwan, and higher than that in Western/Middle Europe.

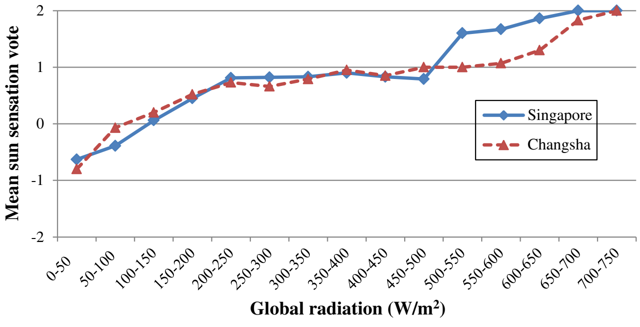


Fig. 4 Sun sensation and global radiation

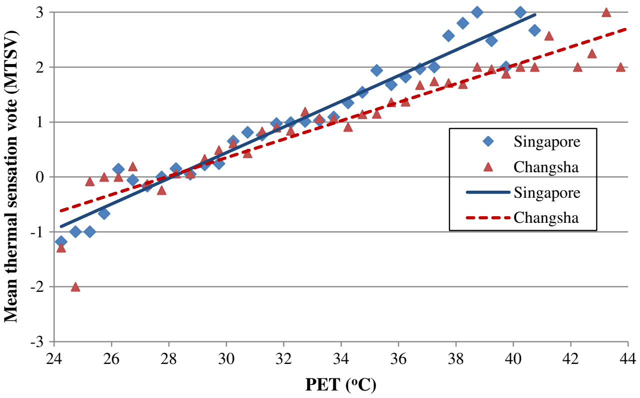


Fig. 5 Regression of thermal sensation and physiologically equivalent temperature (PET)

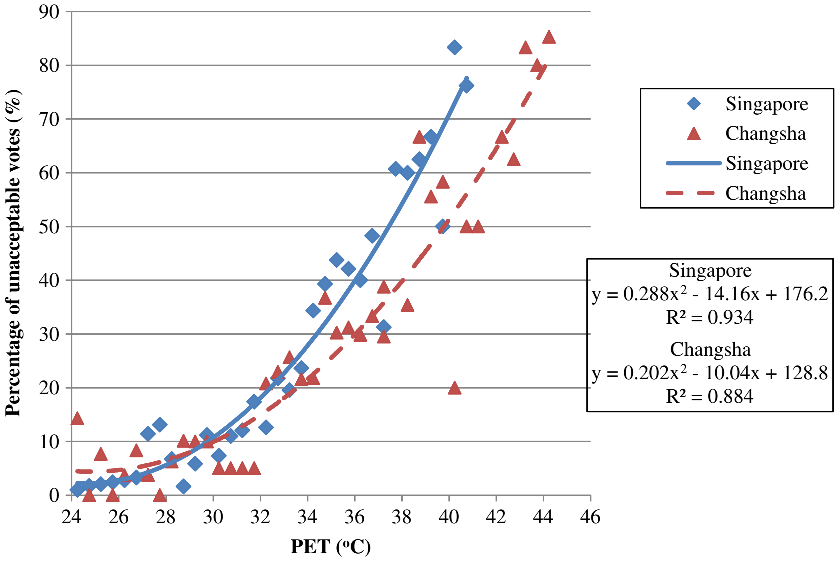


Fig. 6 Thermal comfort range for outdoor environments in Singapore and Changsha

The thermal sensations and PET classes for Singapore can be applicable for other similar tropical regions where the cool/cold discomfort rarely occurred. The PET range for "neutral" thermal sensation is 24–30 °C and the PET range for "warm" thermal sensation is 34–38 °C. PET higher than 42 °C is considered as an extremely hot condition.

Preferred PET

Probit analysis was applied to calculate preferred PET based on thermal preference votes (cooler, no change and warmer). Preferred PET was obtained from the intersection of the two fitted probit lines. Figure 7 shows the probit analysis of preferred PET for both cities. The probit model for requests for cooler was good for Singapore (χ^2=44.100, *df*=32, *p*=0.075) but not good for Changsha (χ^2=111.036, *df*=39, $p<0.001$), while the fit of the requests for warmer to the model was good for Changsha (χ^2=26.041, *df*=39, *p*=0.944) but not good for Singapore (χ^2=51.292, *df*=32, *p*=0.017). The resulting preferred temperatures were 25.2 °C and 22.1 °C for Singapore and Changsha, respectively.

By substituting the preferred temperature into the linear regression Eqs. (1) and (2), we found corresponding TSVs of −0.7 and −1.0 on the ASHRAE scale for Singapore and Changsha, respectively. The result confirms that the people in hot climates may describe their preferred state as cool because the word "warm" implies an undesirable state (McIntyre 1980; Wong and Khoo 2003; Yang and Zhang 2008; Lin 2009).

It can also be seen that although neutral PETs were almost identical in Singapore and Changsha, the preferred PETs were quite different. The preferred PET in Changsha was 3.1 °C lower than that in Singapore. The urgency of expectations regarding comfortable thermal conditions increases with the difference between the neutral and preferred temperature (Hwang and Lin 2007). In Changsha,

Table 7 Thermal sensations and physiologically equivalent temperature (PET) classes for Singapore, Changsha, Taiwan and Western/Middle Europe

Thermal sensation	PET range for Singapore (°C PET)	PET range for Changsha (summer) (°C PET)	PET range for Taiwan [a] (°C PET)	PET range for Western/Middle Europe [b] (°C PET)
Very cold	Not applicable	Not applicable	<14	<4
Cold	Not applicable	Not applicable	14–18	4–8
Cool	Not applicable	Not applicable	18–22	8–13
Slightly cool	20–24	20–24	22–26	13–18
Neutral	24–30	24–31	26–30	18–23
Slightly warm	30–34	31–35	30–34	23–29
Warm	34–38	35–39	34–38	29–35
Hot	38–42	39–43	38–42	35–41
Very hot	>42	>43	>42	>41

[a] Lin and Matzarakis 2008

[b] Matzarakis and Mayer 1996

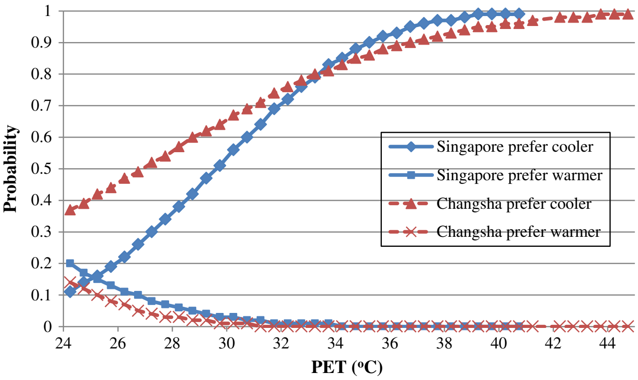


Fig. 7 Probit analysis for preferred physiologically equivalent temperature (PET)

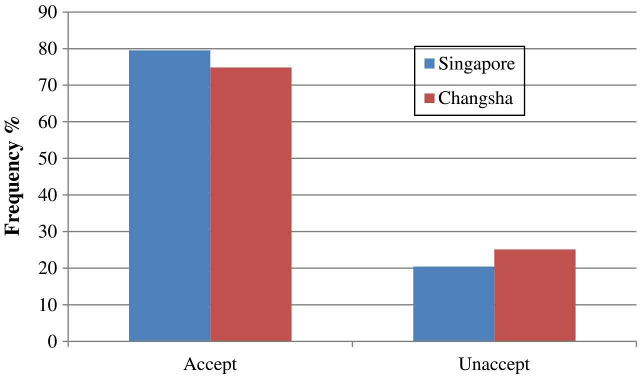


Fig. 8 Overall thermal acceptability assessment

people may feel that 27.9 °C was comfortable, but hope that temperature decreased to 22.1 °C. The difference between what they felt and what they prefered was 5.8 °C. In Singapore, people felt that 28.1 °C was comfortable, but hoped that temperature decreased to 25.2 °C. The difference between what they felt and what they preferred was 2.9 °C. This comparative result demonstrates the impact of expectations on thermal comfort, indicating that the expectation for a low temperature was stronger for respondents in Changsha than respondents in Singapore. This could due to the seasonal effect that people in Changsha experience a cold winter and a mild spring before the summer season, and they may still recall the winter (average air temperature ranges from 4.9 to 7.1 °C) or spring weather (average air temperature ranges from 10.3 to 22.0 °C) during the summer, which may cause them to choose to prefer cooler on a thermal preference scale even when the thermal condition is neutral for them. Another reason for the lower preferred PET in Changsha is that cold discomfort is not an undesirable condition since people in Changsha would prefer to wear heavier clothing in a cooler environment.

Thermal acceptability

Figure 6 shows that under warmer/hotter conditions (PET> 34 °C), at the same PET, the percentage of respondents who feel the thermal condition unacceptable in Changsha was lower than that in Singapore, suggesting that the hot tolerance of Changsha respondents was higher than that of Singapore respondents. T-test also shows that under hot conditions (PET>34 °C), the percentage of thermal unacceptability was significantly lower for Changsha respondents than that for Singapore respondents ($t(1036.980)=3.102$, $p=0.002<0.05$). The result is in agreement with the fact previously stated that Singapore respondents perceived the thermal environment as warmer than Changsha respondents, and thus Changsha respondents may be more tolerant than Singapore respondents under hot conditions. However, the overall thermal acceptability assessment (see Fig. 8) shows that the percentage of respondents who considered it thermally acceptable in Singapore (79.6 %) was slightly higher than that in Changsha (74.9 %).

Based on the above findings, it can be concluded that although Changsha respondents were more tolerant than Singapore respondents under hot conditions, the outdoor thermal environment in Singapore was better accepted than that in Changsha. The lower percentage of thermal acceptability in Changsha may be because the climatic condition in Changsha was hotter than that in Singapore.

Thermal sensation prediction

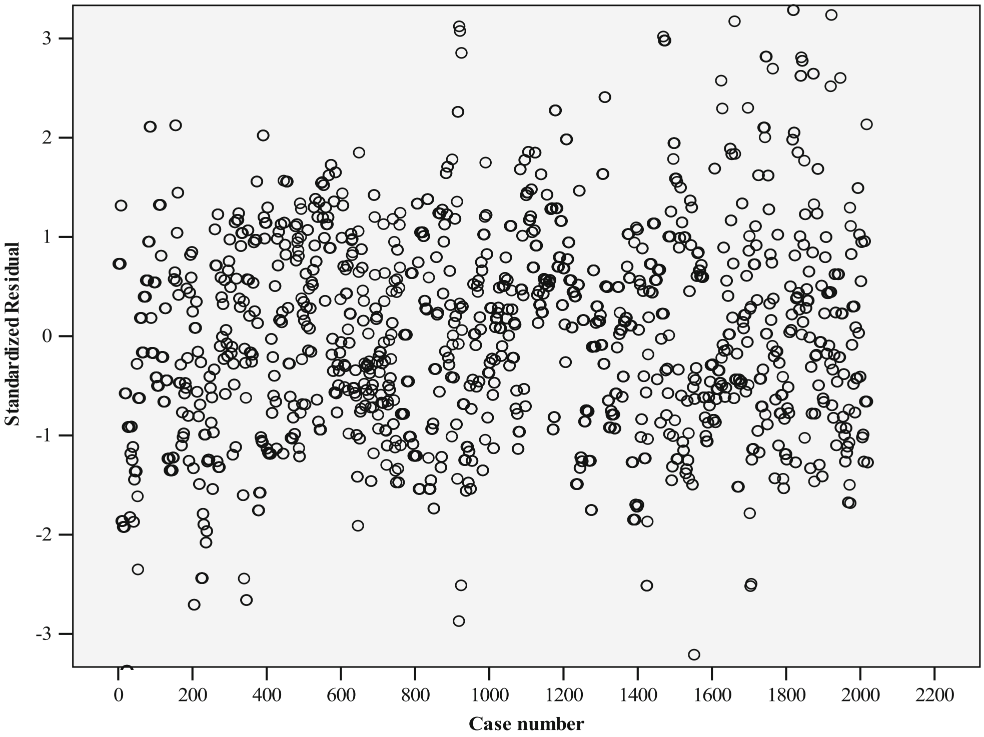
Multiple linear regression was applied to predict respondents' thermal sensation as a function of four independent variables: air temperature (Ta), relative humidity (RH), wind speed (*v*) and mean radiant temperature (Tmrt). Equation (3) was developed based on Singapore data and Eq. (4) was based on Changsha data. Figure 9a, b shows standardized residuals of observed and predicted values for both Singapore and Changsha, respectively. It can be seen that most of the standardized residuals are with ±2, suggesting the fitted models can adequately fit the nature of the observed data.

$$\mathrm{TSV} = 0.398\mathrm{Ta} + 0.023\mathrm{RH} - 0.329 + 0.038\mathrm{Tmrt} - 14.061\left(\mathrm{R}^2 = 0.801\right) \quad (3)$$

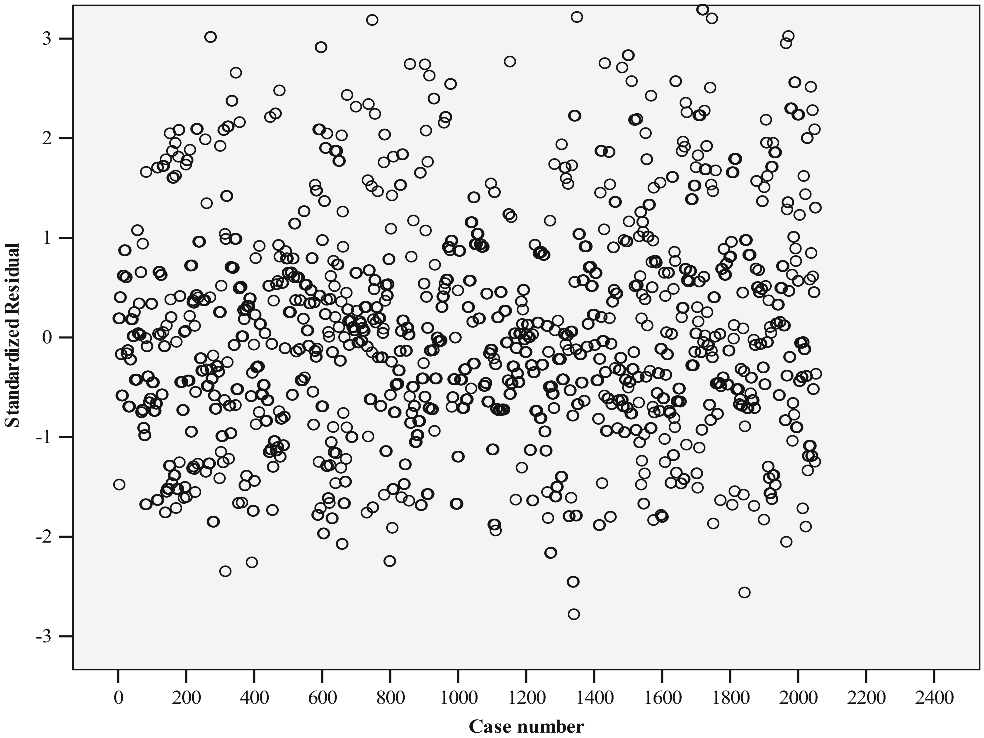
$$\mathrm{TSV} = 0.313\mathrm{Ta} + 0.026\mathrm{RH} - 0.304 + 0.030\mathrm{Tmrt} - 11.622\ \left(\mathrm{R}^2 = 0.552\right) \quad (4)$$

According to the above equations, except wind speed which has a negative sign for the thermal sensation (indicating lowering of the thermal sensation with higher wind speed), air temperature, relative humidity, and mean radiant temperature have positive effects on thermal sensation. That is to say, increase of air temperature, relative humidity, and mean radiant temperature would make people feel warmer, while increase of

Fig. 9 Standardized residuals of observed and predicted thermal sensation



(a) Singapore



(b) Changsha

wind speed would make people feel cooler in hot and humid areas. This is consistent with the findings by Cheng et al. (2012) in Hong Kong which also has a hot and humid climate.

By inputting various combinations of the environmental variables, it can be found that the predicted TSV in Singapore was higher than that in Changsha under the same thermal condition in most cases, which suggests that people in Changsha could be more tolerant with hot conditions than people in Singapore. This result is in agreement with previous thermal acceptability analysis.

It is questioned that the low R^2 of Eq. (4) would affect its applicability. The low R^2 indicates the independent variables can explain only about 55 % of variation of TSV, but the regression coefficient p-values are statistically significant. Figure 9b also shows that the regression model can fit nature of the observed data in Changsha. Besides, a small R^2 does not necessarily imply that estimates of regression models are biased. This is because a small R^2 doesn't imply that the missing factors in explaining TSV are correlated with independent variables that have been included (Colton and Bower 2002).

However, the low R^2 of Eq. (4) suggests that microclimatic variables alone would not be enough to explain human thermal sensation. Thermal adaptation variables like behavioural adjustment, physiological acclimatization, and psychological habituation or expectations (Brager and de Dear 1998; Lin and Matzarakis 2008; Lin 2009) should be included during the process of predicting human thermal sensation. One of the main problems with thermal adaptation variables in thermal sensation prediction is the difficulty of measuring these variables. Thus, future research is greatly needed to evaluate the effect of thermal adaptation variables on human thermal sensation.

It should also be emphasized that Eq. (4) can only be applied to predict TSV in the summer season in Changsha. During other seasons, the outdoor climate condition and respondents' thermal sensation would be different. Future study of outdoor thermal conditions in other seasons in Changsha is needed.

Conclusions

This study compares outdoor thermal environment and outdoor thermal sensation of occupants between Singapore and Changsha, China. The data gathered in this study support the hypothesis that occupants in Singapore and Changsha have different thermal comfort requirements for the outdoor urban spaces despite the similar outdoor thermal conditions.

Subjective analysis shows that respondents generally felt more humid in Singapore than in Changsha within the same vapour pressure range. The optimum wind speeds at each PET range were similar in Singapore and Changsha. However, Changsha respondents were more sensitive to the wind speed than the Singapore respondents. Not much difference was found between the two city respondents regarding the sun sensation.

Although respondents in Singapore and Changsha both well adapted to the hot and humid conditions and had similar neutral temperature (28.1 °C for Singapore and 27.9 °C for Changsha), Singapore respondents were more sensitive to the variations of the PET than Changsha respondents. The acceptable PET for Changsha respondents was slightly wider than that for Singapore respondents. Respondents in Singapore and Changsha had different thermal expectations with the preferred PET of 25.2 °C and 22.1 °C for Singapore and Changsha, respectively. Compared with Singapore respondents, Changsha respondents had a more urgent expectation to be cooler.

The relationship between percentage of thermal unacceptability and PET shows that under hot conditions, at the same PET, the percentage of thermal unacceptability was lower in Changsha than that in Singapore, suggesting that Changsha respondents were more tolerant with hot conditions than Singapore respondents.

The regression models for predicting people's thermal sensation were also proposed for both Singapore and Changsha in this study. The models were expressed by a simple mathematical equation and can be easily applied by urban designers to evaluate the thermal sensation of users under certain outdoor thermal environment.

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