Urban outdoor thermal environment and adaptive thermal comfort during the summer

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Abstract
The outdoor thermal environment is an important factor when measuring the livability of a city. Residents will avoid intense heat by reducing their outdoor activities, which decreases the vitality of a city and increases the energy consumed for air conditioning. Outdoor thermal comfort has a great impact on outdoor activities; therefore, we need to evaluate and design the urban outdoor thermal environments in cold regions to improve the outdoor thermal comfort level. In this study, we conducted a questionnaire survey to assess the outdoor thermal comfort and adaptive thermal comfort in four different urban forms in Xi’an during July 2019, and measuring meteorological parameters, such as the temperature, relative humidity, wind speed, and black bulb temperature. The results are showed as follows. (1) In the cold study area, urban residents generally perceived the outdoor climate as relatively hot during the summer. (2) The participants exhibited psychological and physical adaptations in terms of their thermal comfort. In particular, when the PET was 30 °C, the MTCV was about 1.25 points higher in the later summer period than the early summer period. (3) The neutral PET differs among regions, and it is affected by the climate zone and latitude. Comparisons of our results with thermal comfort studies in different regions such as Singapore and Umeå in north Sweden showed that the thermal comfort is correlated with the regional climate and latitude. The neutral PET is higher in tropical regions. Our findings support the theoretical understanding of adaptive thermal comfort in cold regions and they provide a reference for formulating policies related to adaptive thermal comfort.

Keywords Adaptive thermal comfort · Cold climate · Outdoor thermal Environment · Questionnaire survey · Thermal sensation vote

Abbreviations
PMV Predicted mean vote
UTCI Universal thermal climate index
PET Physiological equivalent temperature
TCV Thermal comfort vote
TSV Thermal sensation vote
MRT Mean radiant temperature
ET Effective temperature
ET* New effective temperature
SET* Standard effective temperature
HIS Heat stress index
WBGT Wet bulb globe temperature
T_a Air temperature, °C
RH Relative humidity, %
V Wind speed, m/s
G Black globe temperature, °C
R Solar radiation, W/m²

Introduction
In urban microclimate design, it is necessary to create a healthy and livable outdoor thermal environment for residents (Marcus and Francis 1997; Ahmed 2003; Thompson and Travlou 2007) in order to increase the utilization of
outdoor space, enhance the vitality of cities, and reduce the energy consumed cooling or heating buildings (Jacobs 2016; Bueno et al. 2012; Lai et al. 2019; He et al. 2009). The outdoor thermal environment in cities is very important for the health of residents. Excessive outdoor temperatures in cities can cause heat stroke and increase the mortality rate, especially among migrant workers, the elderly, and children (Guo et al. 2018; Liss 2015; Wu 2012). Therefore, creating a good urban outdoor thermal environment is very important for building an ecological city.

Many studies have investigated the urban outdoor thermal environment in different climatic regions. In particular, Priyadarsini et al. studied the urban outdoor thermal environment in Singapore in a tropical climate region and found that the facade materials and their color were very important under extremely low wind speeds. The best height/width ratio should be used between high-rise buildings, and it can reduce the temperature by 0.7 °C (Priyadarsini et al. 2008). Yang et al. studied the thermal conditions of the human body in outdoor spaces in Singapore and Changsha, China, and found that the neutral physiological equivalent temperature (PET) was similar for the respondents in the two cities, with 28.1 °C in Singapore and 27.9 °C in Changsha, and the changes in the PET were more sensitive for the respondents in Singapore than Changsha (Yang et al. 2013a, b). In addition, Yang et al. studied urban streets in the central business district of Singapore and found that during the afternoon, the streets facing northwest were more stressful in terms of thermal comfort than those in the northeast–southwest direction (Yang et al. 2016). Johansson et al. studied the thermal comfort of the human body in temperate cities in Ecuador and the influence of the urban microclimate on subjective thermal sensation, and found that the thermal environment accepted by people in tropical areas exceeded the acceptable comfort limit, and the subjective thermal sensation varied over a wide range (Johansson et al. 2018).

Xi et al. studied the effects of different types of design elements on the outdoor thermal environment around urban agglomeration campuses in a subtropical region and confirmed the effects of the sky visual factor and surface heat capacity on the temperature distribution at night (Xi et al. 2012). Spagnolo et al. used questionnaire surveys and comprehensive micro-meteorological instruments to study the outdoor thermal environment in the subtropical region of Sydney (Spagnolo and Dear 2003). Lin et al. studied the influence of pavements on the outdoor thermal environment during the summer and winter in the subtropical region of Taiwan. They showed that the surface temperature of artificial pavement at noon during the summer was 10 °C higher than the surface of vegetation, and the correlation between the surface temperature and air temperature was strong (Lin et al. 2007). Lin et al. evaluated the thermal comfort of urban parks in Taiwan and showed that the attendance rate of people was affected by the sun and thermal environment, and there were close relationships between the thermal sensation vote (TSV), thermal comfort vote (TCV), and thermal environment (Lin et al. 2013). Huang et al. conducted a field study of open spaces in six cities in Wuhan in the subtropical region of China and showed that the outdoor thermal environment strongly influenced the average attendance rate during a period of time (Huang et al. 2016).

Taleghani et al. analyzed the outdoor thermal environment in cities in the Netherlands with a temperate climate and showed that the sunshine hours and average radiant temperature were affected by the urban morphology, and they had the greatest impact on thermal comfort (Taleghani et al. 2015). Givoni et al. discussed the methods used for outdoor comfort research and the problems in the development process (Givoni et al. 2003). Thorsson et al. conducted a survey of the subjective thermal comfort and outdoor activities in parks and plazas in satellite towns in northeastern Tokyo. They showed that the relatively warm thermal environment in the plaza imposed a greater heat load on humans in the plaza compared with parks (Thorsson et al. 2007).

For the subarctic region, Jussila et al. proposed a micro-climate assessment method based on wind comfort analysis and a combination of solar radiation and wind speed, and analyzed the urban thermal environment in the subarctic region of Sweden (Ebrahimabadi et al. 2018). For polar regions, Jussila et al. used a questionnaire to evaluate the feelings of cold and the clothing used by open-pit miners in Finland, Sweden, Norway, and Russia. They found that the clothing choices of open-pit miners in arctic conditions depended on the occupation (outdoor time), environment (temperature, wind, and humidity), and individual factors (cold sensitivity and general health) (Jussila et al. 2017). Færevik et al. found that a cold climate can endanger the heat balance. Protective clothing is important for maintaining thermal comfort and reducing heat loss. The use of advanced technologies such as adaptive temperature and humidity transmission can improve the comfort, work performance, and safety of workers in arctic conditions (Færevik and Wiggen 2014).

Few previous studies have investigated the outdoor thermal environments in areas with cold climates and there is a lack of research into the impacts of different underlying surfaces on residents. In the current increasingly dry and hot climate environment, residents are more often indoors in the summer. Thus, the energy consumed by passive cooling methods such as air conditioning is an important issue due to indoor living and work. Studying the outdoor thermal environment is particularly important for improving urban environmental problems. The research on outdoor comfort is of great significance for improving citizens’ happiness. The quantitative study of thermal comfort has a guiding role in the formulation of indicators at the level of urban planning.
and renovation and renewal at the level of design. In the present study, we considered the city of Xi’an, which is located in the central area of the western basin in China and it has undergone rapid urbanization in recent years. As a consequence, climatic and environmental problems are major issues in Xi’an. Thus, we conducted field tests and questionnaire investigations to assess the impacts of different factors on the outdoor thermal environment under the climatic conditions in Xi’an, and proposed targeted improvements in the thermal environment. The optimized design strategy aims to improve the current outdoor thermal environment in cold regions, and our results also provide scientific data to support related research in areas at the same latitude.

**Methods**

**Study site**

In this study, we explored the impacts of different underlying surfaces on the outdoor thermal environment in cold areas. We considered various underlying surface elements in the area, such as buildings, trees, squares, and lakes, because these different environmental elements can generate different feelings of comfort and happiness regarding heat among residents. Xi’an (34° 18′ N, 108° 56′ E) is located in a cold region of China, with an annual average temperature of 13.7 °C, and outdoor temperature of −3.4 °C in the winter and 30.6 °C in the summer (GB 50736–2012). The research area was Xingqing Campus of Xi’an Jiaotong University, with an area of about 888,800 m², as shown in Fig. 1. The people present in the study area were mainly teachers, students, school infrastructure maintenance personnel, and residents. The questionnaire survey was conducted at four locations in the Fig. 2: (a) small lake side, (b) square, (c) road with big tree, and (d) road without big tree. The questionnaire survey and field test were conducted during July 2019 in the summer research season as Table 2.

**Research indexes**

Many research indicators have been proposed for thermal environment evaluation. Fanger proposed the predicted mean vote (PMV). The PMV thermal comfort model...
comprehensively considers the factors that affect the thermal comfort of the human body and the environment. The PMV has been used widely as an index for evaluating thermal comfort around the world (Fanger 1970; Fanger and Jonassen 1974). The International Association of Biometeorology formulated the universal thermal climate index (UTCI) based on a multi-node model, and it is suitable for all seasons and climate zones (Jendritzky et al. 2012; Blażejczyk et al. 2012; Bröde et al. 2012; Havenith et al. 2012; Blażejczyk et al. 2010). Researchers have also evaluated the thermal environment using indexes such as the mean radiant temperature, effective temperature (ET), new ET (ET*), standard ET (SET*), heat stress index, and wet bulb globe temperature. These indicators have been studied widely and applied in depth. The PET comprehensively considers the main meteorological parameters, such as the temperature, relative humidity, solar radiation, and wind speed, as well as the effects of the metabolic rate, clothing, and individual parameters on thermal comfort. The PET has been used extensively as an indicator in outdoor environment evaluations and research (Matzarakis et al. 1999; Höppe 1999; Matzarakis and Amelung 2008; Deb and Ramachandraiah 2010; Gómez et al. 2013). TCV and TSV are widely used subjective evaluation indicators for indoor and outdoor thermal comfort assessments (Luo et al. 2014; Luo et al. 2015; Wu and Mahdavi 2014; Wang et al. 2017; Feriadi and Wong 2004). In addition, social factors such as thermal adaptability, thermal expectations, age, and gender will affect subjective evaluations of thermal comfort. Considering the specific characteristics of outdoor thermal environment indicators, we used the PET, TCV, TSV, adaptive thermal comfort, thermal expectations, and other indicators to analyze the outdoor thermal environment in Xi’an.

**Survey**

**Questionnaire design**

The questionnaire used in this study had four parts: basic information about participants, outdoor thermal comfort,
happiness, and weather data. The basic information comprised gender, age, education, height, weight, income, occupation, health level, activity level, and clothing. The outdoor thermal comfort was measured using the TSV, TCV, and thermal environment satisfaction, showed in Table 1. The meteorological data comprised the air temperature, relative humidity, wind speed, black bulb temperature, and solar radiation.

Participants

This questionnaire survey was conducted on the Xingqing campus of Xi'an Jiaotong University, which contains spaces such as green parks, commercial plazas, residential quarters, and office buildings. The population in the area mainly comprises students and teachers, staff on and off campus, and residents of communities outside the campus. The participants were mainly aged 20–30 years and they could be regarded as a typical sample of Xi'an as a whole. Therefore, the area was regarded as a typical survey and research area. The questionnaire was conducted as an electronic questionnaire (questionnaire star) and on-site questionnaire. The questionnaire contained multiple choice questions, which were convenient for the respondents to complete. The investigators added the meteorological data, and the research team issued 491 questionnaires. The basic information for the respondents is shown in Table 2, and the survey process is illustrated in Fig. 3.

According to the 2018 Xi’an Statistical Yearbook, the total population of Xi’an in 2017 was 8,459,900 (http://tjj.xa.gov.cn/tjnj/2018/zk/indexch.htm), where the female population was 4.2211 million (49.71%) and the male population was 4.2498 million (50.29%). The respondents to the questionnaire comprised 219 women (44.60%) and 272 men (55.40%), which was similar to the gender distribution of the population in Xi’an.

Meteorological parameters

The outdoor meteorological parameters were measured by the investigator on site. The meteorological parameters comprised the air temperature, relative humidity, wind speed, black bulb temperature, and solar radiation, and the test altitude was about 1.5 m. The test equipment and their parameters are shown in Table 3. All equipment satisfied the requirements of the ISO 7726 standard (1998).

PET

PET is a thermal index based on the Munich Energy Balance Model for Individuals (MEMI), and it is defined as an indoor or outdoor environment where the human skin temperature and internal body temperature reach the same heat as a typical indoor environment, and the PET corresponds to this state (Höppe 1984). In this study, we used Rayman software to calculate PET. $T_{\text{mrt}}$ is an important

| Table 1 Thermal comfort scale |
|-----------------------------|
| -3 | -2 | -1 | 0 | 1 | 2 | 3 |
| cold | cool | slightly cool | neutral | slightly warm | warm | hot |
| -3 | -2 | -1 | 0 | 1 | 2 | 3 |
| very uncomfortable | uncomfortable | slightly uncomfortable | neutral | slightly comfortable | comfortable | very comfortable |
| -2 | -1 | 0 | 1 | 2 | |
| very dissatisfied | dissatisfied | neutral | satisfied | very satisfied |

| Feature | Number | Proportion (%) |
|--------|--------|----------------|
| Gender |        |                |
| Male   | 272    | 55.40%         |
| Female | 219    | 44.60%         |
| Age    |        |                |
| 20 and below | 164 | 33.40%         |
| 21–25  | 192    | 39.10%         |
| 26–30  | 43     | 8.76%          |
| 31–35  | 15     | 3.05%          |
| 36–40  | 24     | 4.89%          |
| 41–50  | 37     | 7.54%          |
| 51–60  | 5      | 1.02%          |
| 61 and above | 11   | 2.24%          |
| Academic degree |    |                |
| Junior high and below | 23  | 4.68%         |
| High school | 80 | 16.29%        |
| Undergraduate | 273 | 55.60% |
| Master   | 69     | 14.05%         |
| Doctor   | 40     | 8.15%          |
| Post-doctoral or above | 6   | 1.22%          |
parameters for calculating PET. $T_{mrt}$ is calculated according to Eq. (1) and following the standard requirements of ISO 7726 (Lin et al. 2007):

$$T_{mrt} = \left[ (T_g + 273)^4 + \frac{1.10 \times 10^8 V^{0.6}}{\epsilon D^{0.4} (T_g - T_a)} \right]^{\frac{1}{4}} - 273$$

(1)

where $D$ is the globe diameter (0.15 m) and $\epsilon$ is the emissivity (0.95 for a black globe).

**Results**

**Microclimatic parameters**

According to the meteorological parameters in the standard year for Xi’an, the study was conducted in the summer (July to August). Figure 4 shows the temperature distribution in the standard year in Xi’an. The daily average temperature fluctuated from 20.29 to 31.74 °C, the daily maximum temperature was 37.90 °C (July 31), and the daily minimum temperature was 17.60 °C (August 27). Figure 5 shows the distribution of the standard annual moisture content in Xi’an, which fluctuated from 7.90 g/kg (July 2) to 22.90 g/kg (August 1), and the average moisture content was 15.95%.

**Thermal comfort in the survey**

**TSV and TCV**

In the survey, 491 questionnaires were issued and according to the completeness of the respondent’s answers to the questions and the accuracy of the information, 491 valid questionnaires were received, with an effective proportion of 100%. The information collected by the questionnaire was analyzed as follows.

Figure 6 shows the distribution of the TSV at the four survey locations. At the small lake side, the thermal sensation was mainly assessed as “neutral” (27.12%) and “hot” (35.59%). In the square, the proportions of “neutral” and “hot” were still relatively high at 36.15% and 32.31%, respectively. At the road with big tree, the thermal sensation was also mainly “neutral” (30.47%) and “hot” (32.03%). At the road with little tree, the thermal sensation was assessed as “neutral” (28.7%), “slightly warm” (22.61%), and “hot” (30.03%). In the four survey locations comprising the small lake side, square, road with big tree, and road with little tree, the percentages of popular votes including slightly warm, warm, and hot were 66.95%, 52.31%, 63.28%, and 59.13%, respectively. Thus, the distribution of the perceptions of the external thermal environment was generally above 50% and in a hot state.
Fig. 4 Standard annual temperatures

![Graph showing standard annual temperatures with days of the year on the x-axis and temperature on the y-axis, indicating daily mean, maximum, and minimum temperatures.]

Fig. 5 Hourly moisture contents throughout a standard year

![Graph showing hourly moisture contents with days of the year on the x-axis and moisture content on the y-axis, indicating specific moisture content values.]

Fig. 6 TSV results

![Graph showing TSV results with categories such as small lake side, square, road with big tree, and road with little tree, with percentage values for different temperature categories.]
The distribution of TCV at the four survey locations is shown in Fig. 7. The two main thermal comfort assessments were “slightly uncomfortable” and “neutral.” The total uncomfortable votes (TCV < 0; slightly uncomfortable, uncomfortable, very uncomfortable) at the small lake side, square, road with big tree, and road with little tree were 38.98%, 40%, 39.85%, and 40.88%, respectively, and all were below 50%, thereby indicating that the participants recognized the comfort of the surrounding thermal environment. The histogram for all types in Fig. 7 shows the overall proportions of TCV survey data. In particular, TCV < 0 votes accounted for 39.92%, TCV = 0 votes accounted for 45.42%, and TCV > 0 votes accounted for 14.66%, and thus the participants were moderately comfortable with the surrounding environment, but some felt slightly uncomfortable.

Figure 8 shows the correlations between the percentage of thermal unacceptability (TCV < 0) and the mean TSV (MTSV) and mean TCV (MTCV). The percentage of thermal unacceptability was consistent with the changes in the MTSV, which was consistent with the MTCV where the opposite trend was found. When the percentage of thermal unacceptability was smallest, the MTCV was largest at 0.36 (“slightly comfortable”) and the MTSV was smallest at 0 (“neutral”). When the percentage of thermal unacceptability was largest, the MTCV was smallest at − 1.14 (“slightly uncomfortable”) and the MTSV was largest at 2.47 (“warm”).

**Thermal unacceptability**

According to the actual outdoor thermal environment in Xi’an, we set a thermal unacceptability percentage lower than 10% as an acceptable range (Chen et al. 2018; Cohen et al. 2013; Lin 2009). Figure 9 shows the quantitative relationship between PET and the thermal unacceptability percentage. According to the regression formula, when the thermal unacceptability percentage was set at 10%, PET was calculated as 20.23 °C.
Neutral PET at different sites

Table 4 shows the correlations between MTCV and PET at the four survey locations. According to Fig. 10, as the PET increased, the MTCV tended to decrease at the four survey locations. When $\text{MTCV} = 0$, the PET value was the neutral PET calculated according to the linear regression formula. The neutral PET values at the small lake side, square, road with big tree, and road with little tree were 26.40 °C, 24.91 °C, 23.47 °C, and 18.40 °C, respectively. The MTCV at all sites also gradually decreased as the PET increased. According to the linear regression equation, the neutral PET over all sites was 23.27 °C in Fig. 11.
**Urban microclimate and TCV**

**Subjective perceptions of participants**

Figure 12 shows the proportions of votes for the most important climate factors. The proportions were highest for the air temperature and solar radiation at the four different survey locations. At the two survey locations comprising small lake side and road with little tree, the participants considered that the air temperature was the most important climate factor, with votes of 44.07% and 45.22%, respectively. At the two survey locations comprising square and road with big tree, the participants considered that solar radiation was the most important factor, with votes of 40% and 41.41%, respectively. Figure 13 shows the voting percentages for the second most important climate factors. Air temperature and solar radiation still had the highest voting rates. At the two survey sites comprising small lake side and road with little tree, the participants considered that solar radiation was the second most important climate factor, with votes of 29.66% and 29.57%, respectively. At the two survey sites comprising square and road with big tree, the participants considered that air temperature was the second most important factor, with votes of 35.38% and 33.59%, respectively.
Correlation analysis

Partial correlation analysis was conducted based on the relationships between TCV and the meteorological parameters in Table 5, where a P value less than 0.05 indicated a significant correlation, and the R values were calculated between the TCV and each parameter. The results showed that at the two survey points comprising small lake side and road with big tree, P < 0.05 for the air temperature and TCV, and thus, TCV had a significant correlation with the air temperature, and the R value (correlation coefficient) was negative. Thus, in the hot summer, there was a negative correlation between the air temperature and TCV, which was consistent with the subjective analysis results. At the road with big tree survey point, P < 0.05 for the relative humidity and TCV, and the significant correlation was negative. At all survey points, P > 0.05 for the wind speed and TCV, and for the black bulb temperature and TCV, and thus, they were not significantly correlated.

Adaptive thermal comfort

Psychological adaptation

People will psychologically adapt to their living environment after a long time (Nikolopoulou and Steemers 2003; Yang et al. 2013a, b; Nasir et al. 2012). Summer is the driest and hardest season in Xi’ an. We divided the summer into early and late periods according to the date and compared the capacity of the participants to psychological adapt to the hot outdoor environment. Figure 14 shows the relationship between PET and MTCV, as well as the regression equations for early and late summer. When the PET was the same (e.g., 30 °C), MTCV was about 1.25 times higher in the later stage than the earlier stage. The degree of sensitivity decreased, thereby confirming psychological adaptation in Xi’an.

We analyzed the thermal expectations at the four different survey locations according to the psychological expectations in terms of the air temperature, solar radiation, relative humidity, wind speed, and other microclimate elements under different PETs, in Figs. 15, 16, 17, 18.

Figure 15 shows the preferences of the participants in terms of the air temperature at PETs of 20–25 °C, 25.1–30 °C, and 30.1–35 °C. At the four different survey locations, the surveyed participants generally hoped that the air temperature would decrease. In Fig. 16, as the PET increased, the participants strongly preferred a decrease in the air temperature, especially in the square area. In the different PET temperature ranges, the participants preferred a reduction in the solar radiation. Figure 17 shows the preferences of the participants in terms of the relative
humidity were quite different. When the PET temperature range was 20–25 °C, the participants preferred that the relative humidity would remain unchanged or decrease. In the other PET temperature ranges, the participants wanted the humidity to remain the same. Figure 18 shows that regardless of the PET temperature range, the participants preferred an increase in the wind speed because the wind speed is low throughout the year in Xi’an, which is located in the Guanzhong Basin.

**Physiological adaptation**

Residents will adapt to the local climate through physiological adjustments. We analyzed the clothing insulation under different PET conditions among the participants, as shown in Figs. 19 and 20. The relationships between the mean PET and mean clothing insulation at all survey locations are shown in Fig. 19. The mean clothing insulation and mean PET were negatively correlated. The participants adjusted...
their amount of clothes to adapt to the local climate conditions. The relationships between the mean PET and mean clothing insulation at each survey site are shown in Fig. 20. At the little tree survey site, when the PET increased to 33.8 °C, the mean clothing insulation decreased to 0.328. At the square survey site, when the PET increased to 34.5 °C, the mean clothing insulation decreased to 0.328. At the big tree survey site, when the PET decreased to 19.9 °C, the mean clothing insulation increased to 0.346. At the small lake side survey site, when the PET increased to 32.7 °C, the mean clothing insulation decreased to 0.320. Thus, the participants adjusted their clothing insulation to overcome outdoor thermal discomfort, and at the same PET, the adjustment of clothing insulation varied among the different survey locations.

Figure 21 shows the adaptive physiological cooling strategies of the participants. We found that 50.31% of the participants preferred to stay cool under big trees, which is consistent with the survey results where the participants wanted more tall trees to be planted in the city. In addition, 42.97% of the participants preferred to drink water at room temperature to cool down. People of different ages
consumed different types of water, where 34.42% preferred to drink ice water and 9.78% wanted to drink hot water. Enjoying the shade of buildings was preferred by 41.14% of the participants, thereby demonstrating that shading by buildings can improve the outdoor thermal environment in the city. Only 9.37% of participants preferred to go to the lakeside, and thus the lake could improve the humidity level of the air and enhance the beauty of the environment, but it could not block solar radiation. Therefore, fewer participants preferred to go to the lakeside. Thus, it is recommended that lakes should be combined with pavilions, willows, and other trees in designs to encourage residents to visit lakes. Moreover, 41.34% of the participants preferred to stay indoors and reduce their frequency of going out, but this increases the energy consumed by indoor air conditioning and refrigeration, which is not conducive to national energy security, as well as reducing urban vitality and leading to the underutilization of urban outdoor space. Therefore, the city should be optimized by improving the outdoor thermal environment according to the utilization preferences of residents.

Optimal outdoor thermal environment design strategy

We conducted a questionnaire survey based on 11 optimization strategies for urban outdoor thermal environments. Figure 22 shows the most important urban outdoor thermal environment cooling strategies selected by the participants, where 63.95% considered that planting rows of big trees on the street could help to achieve a significant cooling effect. Figure 23 shows the second most important urban outdoor thermal environment cooling strategies selected by the participants, where 18.33% considered that water misting in the
Fig. 20 Physiological adaptation at each survey site

![Graph showing physiological adaptation at each survey site with various lines representing different conditions over a period from 1-Jul to 25-Jul.](image)

Fig. 21 Adaptive cooling strategies

![Graph showing adaptive cooling strategies with bars for different activities.](image)
street could reduce the outdoor temperature. For interviewees, big tree, mist and shoal water are all in the top three for cooling strategies, lawn and pedestrian bridge ceiling are considered to be relatively ineffective. This means that in the popular perception, natural cooling measures have a higher psychological effect than artificial ones.

Discussion

In order to confirm that different latitudes have different effects on the PET, we assessed data for Xi’an (34.30° N, 108.93° E; elevation, 397 m), Singapore (1.37° N, 103.98° E; elevation, 16 m), North Sweden (Kiruna; 67.82° N, 20.33° E; elevation, 452 m), Taiwan (Taipei; 25.07° N, 121.55° E; elevation, 6 m), Tianjin (39.08° N, 117.07° E; elevation, 2 m), and five other different regions throughout the year. Monthly average air temperature and monthly average relative humidity data were compared in Fig. 24. The weather data were obtained from the Energyplus website using Climate consultant software. The latitude of Xi’an is 33.52° lower than that of North Sweden. The average air temperature in Xi’an during July is 26 °C, which is 14 °C higher than that in North Sweden (12 °C), and thus, the latitude has a significant influence on the air temperature. In order to study the temperature changes in different climate zones, statistical analysis was conducted for North Sweden in the sub-arctic climate zone, Xi’an and Tianjin in the temperate monsoon climate region, Taipei in the subtropical monsoon climate zone, and Singapore in the tropical rainforest climate zone. The temperatures are similar in Xi’an and Tianjin, where the temperature in July is 26 °C, and the relative humidity levels are 72% and 76%, respectively. The relative humidity in Xi’an is 4% lower than that in Tianjin. We analyzed the annual differences in the temperature and relative humidity in different cities and detected significant differences in the temperature and relative humidity in different climate zones. In particular, the annual temperature differences are 26 °C in Xi’an (0 to 26 °C), 28 °C in Tianjin (−2 to 26 °C), 2 °C in Singapore (26 to 28 °C), 13 °C in Taipei (16 to 29 °C), and 25 °C in North Sweden (−13 to 12 °C). In the different climate zones, the relative humidity
differences are relatively small every year, i.e., 20% in Xi’an (57 to 77%), 28% in Tianjin (49 to 77%), 8% in Singapore (80 to 88%), 9% in Taipei (76 to 85%), and 15% in North Sweden (68 to 83%). Thus, the relative humidity differs significantly among different climatic regions.

Table 6 shows the neutral PET values in the five regions (Xi’an, Singapore, Umeå in North Sweden, Taiwan, and Tianjin). In summer, the neutral PET in Xi’an is 5.43 °C and 6.07 °C lower than those in Singapore and Taiwan, respectively, thereby confirming that the residents of Xi’an (cold climate zone) must adapt to colder climates than the residents of Singapore (tropical zone) and Taiwan (hot summer and warm winter zone). In addition, the neutral PET in Xi’an is 9.97 °C and 7.72 °C higher than those in Umeå in North Sweden (subarctic climate zone) and Tianjin (cold climate zone), respectively. These findings are consistent with those obtained by Xin Chen (Chen et al. 2018), Pninit Cohen (Cohen et al. 2013), and Tzu-Ping Lin (He et al. 2009).

We analyzed the PET and TSV data for the five different regions comprising Xi’an, Singapore, Umeå, Taiwan, and Tianjin in Table 7, and found that the TSV in Xi’an ranges from −3 to 41 °C, i.e., 44 °C, which is 20 °C higher than in Singapore, 16 °C higher than that in Taiwan, and 18 °C lower than that in Tianjin. Thus, residents who live in areas with large annual temperature differences for a long time have a high capacity to adapt to the thermal environment and their acceptable temperature range is wider. The lowest TSV temperature is −3 °C in Xi’an, which is 22 °C and 17 °C lower than those in Singapore and Taiwan, respectively.

![Comparison of temperature and relative humidity in different regions](image)

**Table 6** Neutral PET in summer in different regions (°C)

| Regions          | Xi’an (Yang et al. 2013a, b) | Singapore (Yang et al. 2017) | Umeå, North Sweden (Yang et al. 2013a) | Taiwan (Lin et al. 2011) | Tianjin (Lai et al. 2014) |
|------------------|------------------------------|------------------------------|----------------------------------------|--------------------------|-------------------------|
| Neutral PET      | 23.27                        | 28.70                        | 13.30                                  | 29.34                    | 15.55                   |

Fig. 24 Comparison of temperature and relative humidity in different regions.
and 13 °C higher than that in Tianjin. Residents who live in subtropical regions are highly adaptable. The highest TSV temperature is 41 °C in Xi’an, which is close to that in the other five regions, i.e., 2 °C higher than those in Singapore and Umeå, and 1 °C and 5 °C lower than those in Taiwan and Tianjin, respectively. These results are very interesting because they show that there is a limit to temperature perception by the human body. Thus, irrespective of whether residents live in tropical, subtropical, temperate, or sub-polar climate zones, the maximum acceptable temperature limit is basically between 39 and 46 °C, which is very high. These high temperatures can cause physical illness and even death.

### Conclusion

In this study, we conducted a questionnaire survey to assess the outdoor thermal comfort and adaptive thermal comfort among people at five different locations on Xingqing campus of Xi’an Jiaotong University in Xi’an and the surrounding area. In addition, the temperature, humidity, and other environmental parameters were determined using equipment at the same time that the questionnaires were completed. We analyzed the thermal perceptions of the participants and thermal comfort acceptance of the surrounding environment in different areas to determine the factors that influenced outdoor thermal comfort, and our conclusions can be summarized as follows.

1. In the cold study area, urban residents generally perceived the outdoor climate as relatively hot during the summer. The four survey locations at the small lake side, square, road with big tree, and road with little tree were all voted as hot (including slightly warm, warm, and hot), i.e., by 66.95%, 52.31%, 63.28%, and 59.13% of the participants, respectively, and all of these values exceeded 50%. In terms of the comfort of the surrounding environment, the proportions of the participants at the small lake side, square, road with big tree, and road with little tree survey areas who voted for uncomfortable (TCV < 0; slightly uncomfortable, uncomfortable, and very uncomfortable) were 38.98%, 40%, 39.85%, and 40.88%, respectively, and all were below 50%, thereby indicating that they recognized the discomfort of the surrounding thermal environment. In addition, the air temperature and solar radiation were important climatic factors that affected the thermal comfort of the participants.

2. The participants exhibited psychological and physical adaptations in terms of their thermal comfort. In particular, when the PET was 30 °C, the MTCV was about 1.25 points higher in the later summer period than the early summer period. In terms of thermal expectations, residents preferred that the temperature and solar radiation would decrease, and that the wind speed would increase. In terms of their physiological adaptability and thermal comfort, residents increased or decreased their amount of clothes according to the environmental temperature in order to adapt to the changing thermal environment. Irrespective of whether the climate zone is a subarctic climate zone, temperate monsoon climate region, subtropical monsoon climate zone, or tropical rainforest climate zone, there is a limit to the adaptability of the human body to the outdoor thermal environment.

3. The neutral PET differs among regions and it is affected by the climate zone and latitude. For example, the neutral PET is 23.27 °C in the cold area of Xi’an, 28.70 °C in the tropical area of Singapore, 29.34 °C in the subtropical region of Taiwan, and 13.30 °C in Umeå in the subarctic climate zone. The neutral PET differs significantly among different climate zones and latitudes.

In this study, we explored the thermal perception and thermal comfort of urban residents in Xi’an in a cold region, and contributed to research into thermal environment assessment in cold regions. Our results provide an important reference to facilitate significant improvements in the current urban outdoor thermal comfort level. Compared with other studies that mainly consider urban area simulation, this paper comprehensively considers the interviews of urban...
residents and on-site assessment of underlying surface, which has a more comprehensive dimension for studying the relationship between thermal comfort and urban design. The results of this study will provide indicators and suggestions for outdoor thermal comfort for urban planning or urban renewal for city planners and architects. At the same time, it will also play a certain reference role in the future research of outdoor microclimate simulation.

**Future work**

For the future study, further analyses of thermal comfort should be conducted in different age groups. In addition, other underlying surface types that were not covered in this study in Xi’an require investigation in future research.

**Author contribution** Professor Meng Zhen wrote the paper. Weihan Zou and Rui Zheng completed the questionnaire survey. Professor Yujie Lu modified the paper.

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**Data availability** All our data and materials are available.

**Declarations**

**Ethical approval** The questionnaire in this survey got ethical approval.

**Consent to participate** The paper has the consent to participate this journal.

**Consent for publication** All authors agree to publish this paper.

**Conflict of interest** The authors declare no competing interests.

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