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Outdoor Thermal Sensation and Thermal Comfort in Xi'an

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ABSTRACT

To study the current situation of outdoor thermal comfort in Xi'an, this research conducted a questionnaire survey from April to May 2019. The questionnaire included basic information, thermal sensation, thermal comfort and thermal expectations of the respondents. A total of 248 valid questionnaires were returned. Survey results indicated that the thermal comfort characteristics across gender, age, educational background, height and weight were analysed and climate differences in typical cities in five climate zones were compared and evaluated. Results showed that women are more sensitive to thermal sensation and thermal comfort than men. The respondents aged 31–35 have the lowest and highest sensitivities to thermal sensation and thermal comfort, respectively. Below undergraduate respondents have the highest and highest sensitivities to thermal sensation and thermal comfort, respectively. Body mass index is positively correlated with thermal sensation. When thermal sensation increases, the respondents expect that the temperature and solar radiation are decreased but wind speed and relative humidity are increased. Xi'an has large geographical differences with cities in other climate zones, thereby indicating that outdoor thermal comfort has significant regional differences.
Keywords: Outdoor thermal environment; Questionnaire survey; Thermal comfort; Thermal sensation; Cold area

Introduction

The improvement in the standard of living of people has resulted in an increase in their requirements for the environment. Apart from suitable facilities and landscape, a comfortable outdoor thermal environment can improve the efficiency of urban space use. Therefore, thermal comfort has gradually become an important factor in optimising architectural design and urban planning.

Human thermal comfort represents a state of mind that expresses satisfaction with the thermal environment (ASHRAE 1992). The traditional thermal comfort theory is based on the balance between human body heat production and loss (Nikolopoulou and Lykoudis 2006). Hence, designing effective standards and models can effectively deepen the understanding of the thermal environment. Over the past few decades, over 100 indicators have been developed to assess human thermal comfort (Blazejczyk et al. 2012). Different meteorological, geographical,

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psychological and socio-cultural factors have led to varied understanding of thermal comfort across regions (Kovács et al. 2016). Therefore, a single index cannot accurately describe the thermal environment characteristics of all regions. Most of them are only applicable to the place of development (Europe or the US). Accordingly, accurately grasping the local thermal environment will help improve environmental comfort and building energy consumption. Moreover, numerous studies have focused on the local thermal environment. A few of these studies have calibrated the existing thermal comfort indices (Lin and Matzarakis 2008; Cohen, Potchter and Matzarakis 2013), whereas others have discussed the characteristics of the local thermal environment and how to improve comfort (Ridha, Ginestet and Lorente 2018; Spangenberg et al. 2019).

The existing research has the following characteristics and limitations. (1) The research on indoor thermal environment outnumbers those on outdoor thermal environment because many people spend more time indoors than outdoors; the indoor thermal environment is likewise easy to control (Höppe 2002; De Dear and Brager 1998). (2) The majority of the related studies have focused on temperate and subtropical climates (Lin et al. 2013; Ng and Cheng 2012), whereas only a few studies on cold climates have been conducted. On the basis of the national standard Thermal Design Code for Civil Buildings (GB50176-51993 1993), China is divided into five climatic zones (i.e. severe cold, cold, hot summer and cold winter, hot summer and warm winter, and temperate zones). The majority of the studies on Chinese cities have concentrated on the hot summer and cold winter or hot summer and warm winter zones (Yin et al. 2012; Zeng and Dong 2015). Only a few studies on the cold zone, mainly in economically developed regions in Northern China, such as Tianjin (Lai et al. 2014), have investigate the Northwest Territories. (3) In the majority of the related studies, establishing and calibrating thermal comfort models are based on the use of the thermal sensation vote (TSV) as a ruler (Lin 2009). Thus, thermal comfort is a subjective concept, which differs in the understanding of different regions, cultures and crowds. That is, the relationship amongst thermal sensation, thermal comfort and respondent information should be identified.

Xi'an is a typical city in China's cold zone and an important central city in the country's northwestern region. This study used a questionnaire survey to analyse the current status of outdoor thermal environment in Xi'an from April to May 2019. This research aims to investigate and compare the thermal comfort characteristics of different people in the cold zone and compare these characteristics with typical urban meteorological parameters in other climate zones.

Methods

Research Site and Personal Information Survey

A questionnaire survey was conducted in the Qujiang campus of Xi'an Jiaotong University from April to May 2019. The total area of the campus is approximately 12,000 m^2 and the university's function is mainly based on scientific research.

The total number of survey respondents was 264 and were mainly school teachers and students. The respondents were composed of 162 men and 102 women with the age range concentrated below 35 years old (approximately 85%).

The background survey of the respondents indicated that they generally achieved higher education and over 93% of the respondents obtained a bachelor's degree or above. The highest proportion is 40.9% for bachelor's degree and 37.5% for doctoral degrees or above.

Additionally, we investigated the physical condition of the respondents. Over 95% of the respondents were in good health and above and the questionnaires of the uncomfortable respondents were excluded in the statistical process. The respondents' physical condition showed that those with height of above 170 cm accounted for 57.1% and those with weight of over 60 kg accounted for 60.2%.

Questionnaire Design

The questionnaire used in this study consisted of Part A, which is a survey on respondent information; and Part B, which is an evaluation of thermal comfort. Part B includes the following parameters:

(1) TSV uses the seven-point scale recommended by ASHRAE-55 2013 (ASHRAE 2013): cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (+1), warm (+2) and hot (+3). The respondents were asked to vote separately for the thermal sensation of the Xi'an outdoors.

(2) Thermal comfort vote (TCV) uses a seven-point scale as follows: very uncomfortable (−3), uncomfortable (−2), slightly uncomfortable (−1), neutral (0), slightly comfortable (+1), comfortable (+2), and very comfortable (+3).

(3) Thermal expectation vote uses four meteorological parameters by designing a three-level ruler, namely, increase (+1), no change (0), and decrease (−1), and requiring the respondents to vote on how the four meteorological parameters are expected to change.

Survey Campaign

Information from the returned questionnaires was initially processed and statistical results were analysed using SPSS17.0.

We considered at least one of the following methods in discussing the effects of a single element on thermal sensation and thermal comfort.

(1) We took the average of the votes corresponding to different options and used image or regression analysis to determine the relationship. For example, each option for age was counted as a set of mean thermal sensation vote (MTSV) and an image was drawn on the bases of the data to visually display the impact of each element.

(2) We used a different set of options to draw a scatter plot of all the respondents with TSV and TCV as the independent and dependent variables, respectively, and fit the straight line to intuitively compare the influences of each option.

To further analyse the meteorological characteristics of Xi'an, we selected typical cities from four other climate zones in China and compared their climate data with those of Xi'an in the cold area (climate data were derived from Climate Consultant 6.0 and DeST 2.0).

Discussion and Results

Thermal Comfort Characteristics of Different Groups of People

We analysed different personal factors (i.e. gender, age, educational background, height and weight) to study the thermal comfort characteristics of different groups of people.

Gender. Figure 1 depicts the distribution of MTSV and MTCV across gender. In terms of MTSV, men and women reached 0.71 and 1.23, respectively, with a difference of 0.52. This result indicates that women are more sensitive to thermal sensation than men. In terms of MTCV, men and women are −0.27 and −0.02, respectively, with a difference of 0.25, thereby indicating that men have higher requirements for thermal comfort than women.

Figure 2 illustrates the relationship between TSV and TCV across gender. The slope indicates that women's thermal comfort is higher than that of men under different thermal sensation. That is, thermal comfort for women generally changes with a change in thermal sensation, thereby indicating that women are more sensitive to thermal comfort than men.

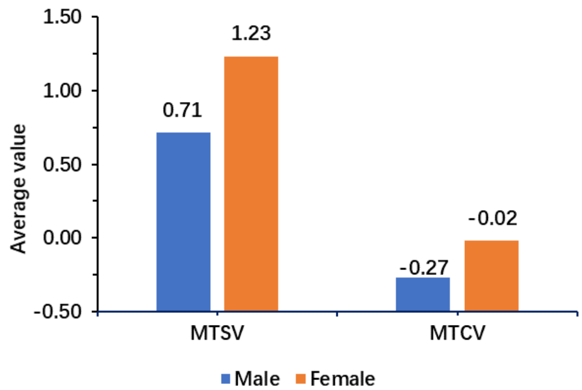

Figure 1. MTSV and MTCV across genders

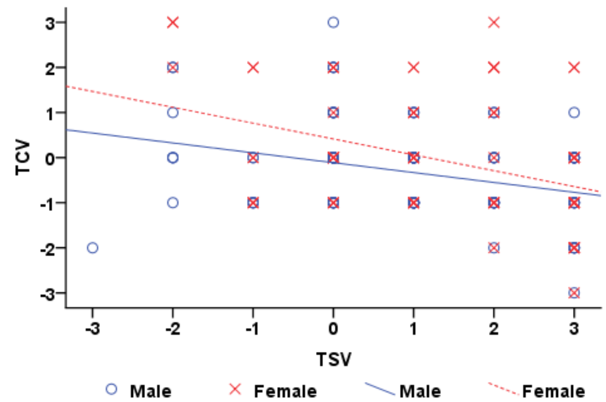

Figure 2. Relationship between TSV and TCV across genders

Age. Figure 3 indicates that MTSV shows a trend of 'initial drop and increase'. The valley value (0.59) and peak value (1.57) of MTSV pertain to the respondents aged 31–35 years and 41–50 years, respectively, with a difference of 0.98. This finding shows that people aged 41–50 years and 31–35 years have the highest and lowest sensitivities, respectively, to thermal sensation.

Figure 4 depicts the relationship between TSV and TCV across age groups. The thermal comfort of the three age groups, namely, 35 to 50 years, under 25 years and over 50 years is arranged from high to low. The overall trend is similar, thereby indicating that the three age groups have similarities in the perception of thermal sensation and thermal comfort. When thermal sensation changes, the 25–35 year respondents experience the most changes in thermal comfort. Additionally, the slope for this group differs from those of the other age groups, thereby indicating that this age group is considerably sensitive to thermal comfort.

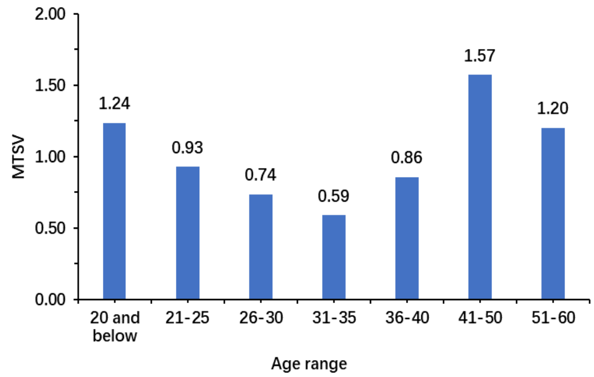

Figure 3. MTSV across age groups

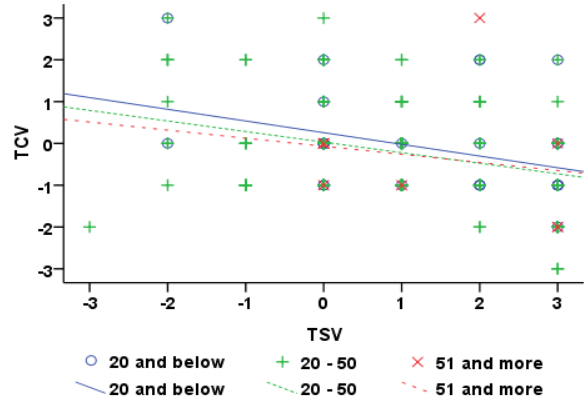

Figure 4. Relationship between TSV and TCV across age groups

Educational background. Figure 5 shows that MTSV is highest (1.40) and lowest (0.58) for the respondents who are below undergraduate and with master's degrees, respectively, with a difference of 0.82. The MTSV values are 1.08 and 0.78 for the respondents with bachelor's degrees and PhDs and above, respectively. This result indicates that the former is considerably sensitive to thermal sensation.

Figure 6 depicts the relationship between TSV and TCV of the respondents with different educational backgrounds. Those with bachelor's and master's degrees and PhDs have similar thermal comfort trends (that are decreasing). The trend of the below undergraduate respondents differs. That is, when thermal sensation changes, their thermal comfort changes decreases.

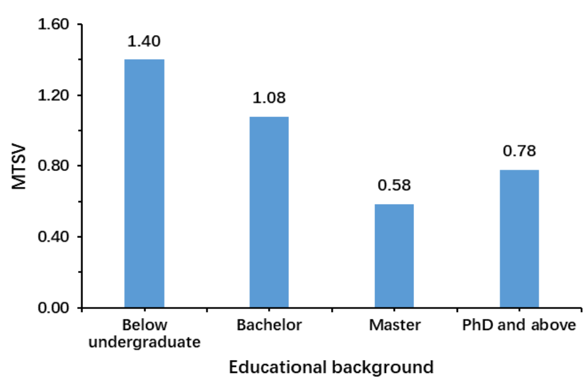

Figure 5. MTSV across educational backgrounds

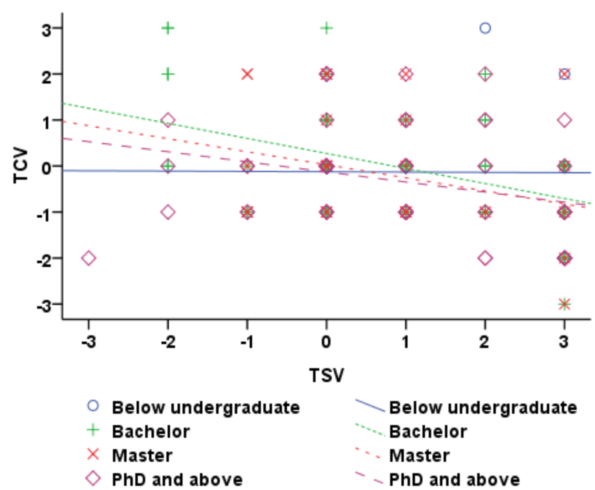

Figure 6. Relationship between TSV and TCV across educational backgrounds

Body mass index. This study uses body mass index (BMI), which is weight divided by the square of height, to measure the physique of the respondents. We referred to the China Standard

BMI (see Table 1) to divide the respondents into groups of 18.5 and below, 18 to 19.5, 19.5 to 21, 21 to 22.5, 22.5 to 24 and 24 and above. Their MTSV values were obtained.

Table 1. China Standard BMI

BMI	Evaluation	BMI	Evaluation
Below 18.5	Underweight	18.5 to 23.9	Normal weight
23.9 to 28	Overweight	Above 28	Obesity

Figure 7 shows that BMI is positively correlated with MTSV, with R^2 and slope values of 0.36 and 0.05, respectively. That is, the higher the BMI value, the higher the respondents' thermal sensation.

Figure 8 shows that thermal comfort decreases with an increase in thermal sensation for the underweight (BMI < 18.5) respondents, although the variation is minimal. For the normal weight respondents (18.5 < BMI < 23.9), thermal comfort decreases with an increase in thermal sensation, although the variation range is large. For the overweight respondents (BMI > 23.9), thermal comfort value remains nearly constant with an increase in thermal sensation.

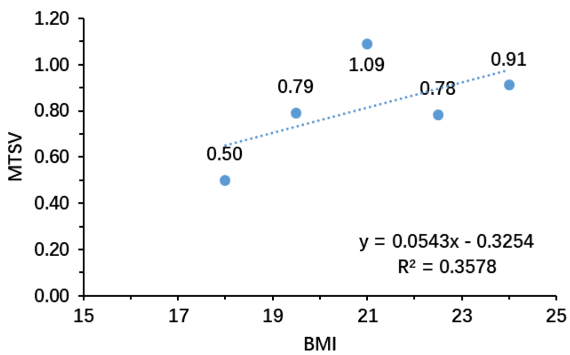

Figure 7. MTSV across BMI values

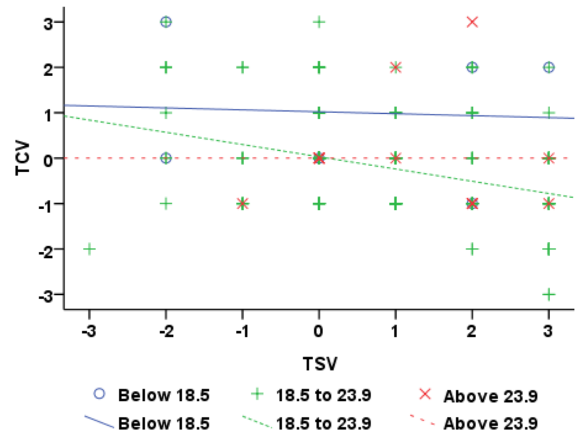

Figure 8. Relationship between TCV and TSV across BMI values

Impact of Meteorological Parameters on Thermal Comfort

Studies have shown that meteorological parameters affecting thermal comfort include temperature, relative humidity, wind speed and solar radiation (Mayer 1993). Therefore, the present study uses thermal expectation to analyse the impact of the four parameters on thermal sensation.

Temperature. Figure 9 shows that TSV is negatively correlated with thermal expectation (temperature) with R^2 and slope values of 0.66 and −0.14, respectively. This result indicates that the larger the TSV, the more the temperature is expected to decrease.

Solar radiation. Figure 10 shows that TSV is negatively correlated with thermal expectation (solar radiation) with R^2 and slope values of 0.86 and −0.13, respectively. This result indicates that the larger the TSV, the more the solar radiation is expected to decrease.

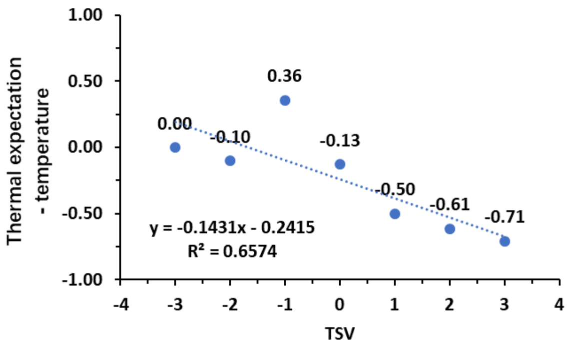

Figure 9. The relationship between thermal expectation (temperature) and TSV

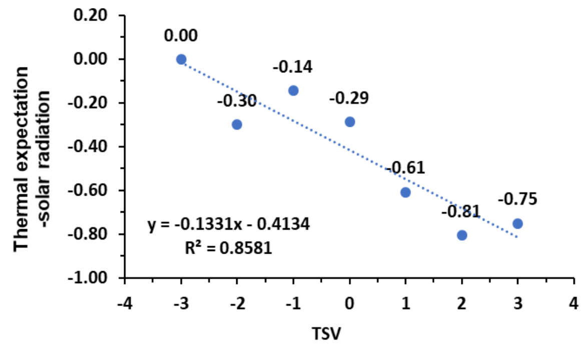

Figure 10. The relationship between thermal expectation (solar radiation) and TSV

Wind speed. Figure 11 illustrates that TSV is positively correlated with thermal expectation (wind speed) with R^2 and slope values of 0.71 and 0.21. This result implies that the larger the TSV, the more the wind speed is expected to increase.

Relative humidity. Figure 12 shows that TSV is positively correlated with thermal expectation (relative humidity) with R^2 and slope values of 0.71 and 0.21, respectively. This result indicates that the larger the TSV, the more the relative humidity is expected to increase.

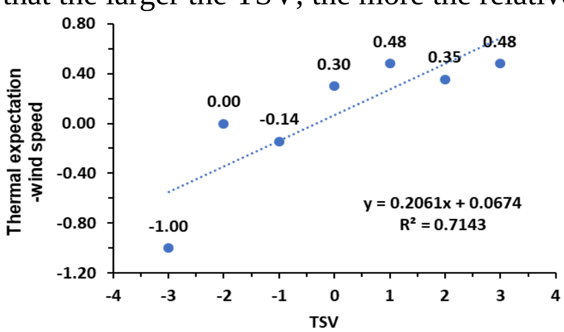

Figure 11. Thermal expectation (wind speed) and TSV

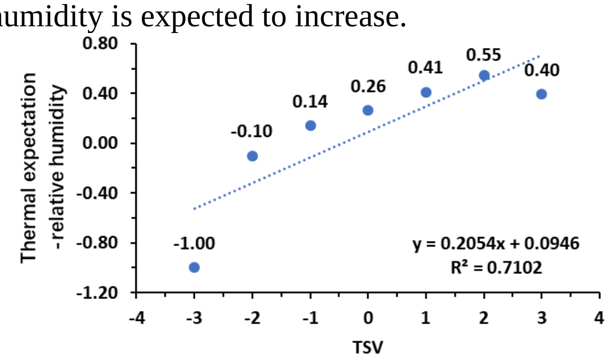

Figure 12. Thermal expectation (RH) and TSV

The fitting line of temperature and solar radiation are below 0. This outcome indicates that the respondents perceive Xi'an as having high temperature and strong solar radiation from April to May and expect them to decrease.

Regional Differences in Thermal Comfort

The team listed the climate data in Xi’an (cold) during the survey period and typical cities in the other four climate zones, namely, Harbin (severely cold), Shanghai (hot summer and cold winter), Guangzhou (hot summer and warm winter) and Kunming (temperate) and compare their climate data.

Temperature. Figure 13 shows that the average temperature in Xi'an is 18.13 °C, which is 6.12 °C lower than that in Guangzhou with the highest average temperature (24.25 °C) and is 7.11 °C higher than that in Harbin (11.02 °C) with the lowest average temperature.

Solar radiation. Figure 14 shows that Xi'an has an average solar radiation of 185 W/m^2, which is 130.5 W/m^2 lower than that in Harbin with the strongest solar radiation (315.5 W/m^2) and is 104.5 W/m^2 higher than that for Guangzhou with the weakest solar radiation (80.5 W/m^2).

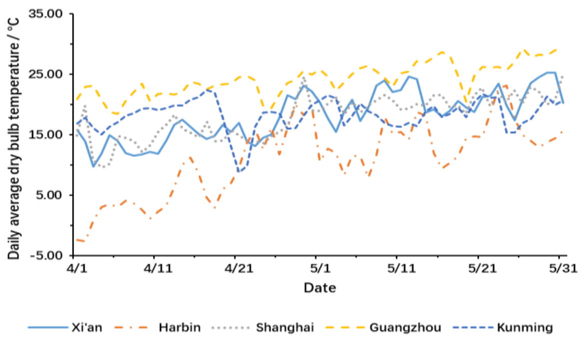

Figure 13. Average dry bulb temperature in five cities

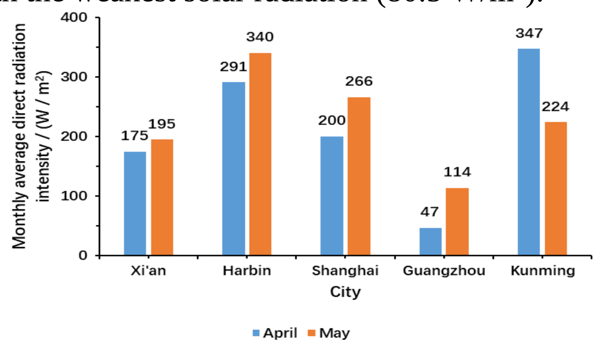

Figure 14. Average direct solar radiation in the five cities

Wind speeds. Figure 15 shows that the average wind speed in Xi'an is 1.5 m/s, which is 1.5 m/s lower than those in Harbin and Shanghai with the highest wind speed (3 m/s) and is 0.5 m/s higher than that for Guangzhou with the lowest wind speed (1 m/s).

Moisture content. Figure 16 shows that Xi'an has an average moisture content of 8.80 g/kg, which is 7.05 g/kg lower than that in Guangzhou with the highest moisture content (15.85 g/kg) and is 4.40 g/kg higher than that in Harbin with the lowest moisture content (4.40 g/kg).

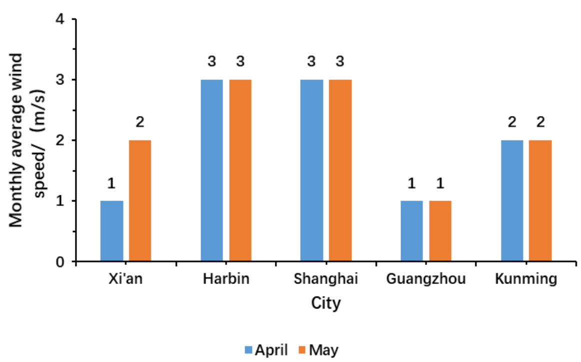

Figure 15. Monthly average wind speed in five cities

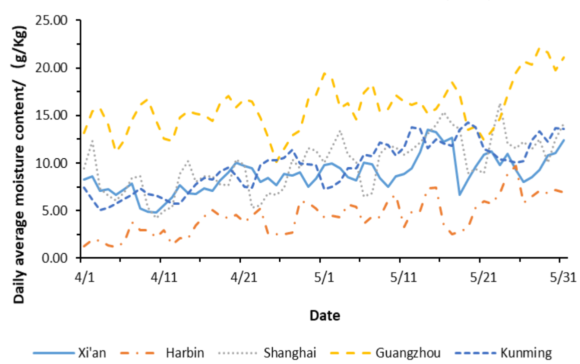

Figure 16. Daily average relative humidity in five cities

The climate data analysis indicates that Xi'an has high temperature, strong solar radiation and low wind speed and moisture content from April to May. Significant differences exist in the meteorological characteristics of typical cities with the other four climate zones, thereby indicating that a regional difference exists in terms of thermal comfort.

The existing research has indicated that increasing urban green plants has a significant effect on improving such thermal environments and thermal comfort in urban areas (Vanos et al. 2019). This method is called green cooling island.

Conclusions

This study conducted a questionnaire survey from April to May 2019 and aimed to understand the outdoor thermal comfort characteristics across groups of people in the cold zone of China. The following conclusions are based on the analysis of the survey results and comparison with other typical cities.

In the comparison of thermal comfort amongst groups of people in terms of gender, women are more sensitive to thermal sensation and thermal comfort than men. In terms of age, the respondents aged 31–35 have the lowest and highest sensitivities to thermal sensation and thermal comfort, respectively. In terms of educational background, the below undergraduate respondents have the highest and lowest sensitivities to thermal sensation and thermal comfort, respectively. BMI was positively correlated with thermal sensation. The respondents with normal body weight are most sensitive to thermal comfort.

In the research on thermal expectation, the findings show that the respondents expect decreases in temperature and solar radiation and increases in wind speed and relative humidity with the increase in thermal sensation. Respondents perceive that Xi'an has a higher temperature and stronger solar radiation in April and May and expect them to decrease.

In the comparison with typical cities in the five climate zones, Xi’an in the cold zone has large geographical differences compared with the other cities, thereby indicating significant regional differences in outdoor thermal comfort. Compared with the other cities, Xi’an has high temperature, strong solar radiation and low wind speed and moisture content from April to May.

Acknowledgements

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