The impact of heatwaves on human perceived thermal comfort and thermal resilience potential in urban public open spaces

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The impact of heatwaves on human perceived thermal comfort and thermal resilience potential in urban public open spaces

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Abstract

Climate change increases the likelihood of heatwave events, causing human thermal discomfort and even mortality. However, it is not clear to what extent humans with long-term and short-term experience of hot-summer exposure can adapt to thermal comfort in urban public open spaces when both experience their heatwave periods. This study aims to investigate outdoor perceived thermal comfort in urban public open spaces during heatwave periods between two groups of people who have long-term and short-term experience of hot-summer exposure. Field surveys were conducted in public squares and parks during the heatwaves in Chongqing, China and Reading, the UK. Chongqing is known as a 'furnace city' and people have been living in a hot summer for a long time, while in Reading the summer is warm and people unusually experience the heatwave. The main results show that Chongqing respondents living in a hot climate for a longer period can endure more heat than Reading respondents during the heatwaves, indicating that Chongqing respondents have more thermal resilience. Besides, different behavioural adaptation measures show that people are active participants to choose their thermal preferences, rather than passive recipients of the thermal environments. The research implication contributes that protective measures against heatwaves need to be taken for pedestrians, including more shaded places with efficient ventilation design for sheltering and handy facilities such as drinking fountains and water spray. The research has novelty in

deepening the dynamic theory of human thermal comfort and providing empirical evidence of thermal adaptation in extreme-high temperature events.

Keywords

Extreme heat events; Thermal adaptation; Thermal Sensation Vote; Universal Thermal Comfort Index; Public square; Park

1 Introduction

1.1 Climate Change and the Facts of heatwave impacts

Climate change increases the likelihood of heatwave events, posing great threats to human health as well as resulting in increased mortality and human thermal discomfort (Painter et al., 2021; Xu et al., 2022; Xu et al., 2016). The occurrence and intensity of heatwave events could vary depending on the region's climate type (WMO & WHO, 2015). More importantly, urban heatwave issues combining the effects of global warming and Urban Heat Island (UHI) becomes a critical problem for worldwide cities in recent years (He et al., 2022; Iping et al., 2019). Heatwaves would make the UHI intensity substantial, bringing heat-related health risks for city dwellers (Macintyre et al., 2018). As for Asian cities, in China, heatwaves cause severe health impacts and are vulnerable to females, the elderly, and illiterates (Yang et al., 2019). There were also frequent heatwaves and heat stress in happened in the summers in major metropolitan cities of India (Kumar et al., 2022). In the Global South, urban heat would increase the vulnerability of informal settlement residents to heat-related morbidity and mortality in Africa (Pasquini et al., 2020). Even in far northern Europe, the climate in 2050 has been predicted to become warmer in the warmest month (Venter et al., 2020). It turns out that in 2019 European summer heatwaves in Germany, the Netherlands, and the UK experienced record-breaking temperatures exceeding normal by 4.7℃ (Ma et al., 2020). In 2020, UK heatwaves back again in June and August caused more than 2000 deaths (PHE, 2020; Thompson et al., 2022).

1.2 Thermal resilience and human adaptation to perceived thermal comfort

1.2.1 The conception of thermal resilience

For hazard mitigation and against climate change impacts in the built environment, resilience has gained increasing attention (McAllister, 2013). Resilience, by the definition from an ecological perspective, "is the ability of a system to adjust in the face of changing conditions" (Pickett et al., 2004). Because the ecological framing of resilience is suitable for urban regions for their dynamic, complex, and adaptive ecosystems, instead of static engineering resilience (Meerow & Newell, 2019). Adaptability is a part of resilience, representing the capacity to adjust responses and allow for development along the current trajectory (Folke et al., 2010). Derived from the conceptual relationship between resilience and adaptation, it can be deduced that thermal adaptation only contains human's ability to adapt to thermal comfort, while thermal resilience includes not only human's adaptability to thermal comfort but also the urban spatial dimension that is designed by humans for providing climate-adaptive strategies.

Thus, thermal resilience includes the ability of two systems including the human dimension and the spatial dimension to endure heat and adapt to heatwaves. The former dimension indicates the system of human adaptation to thermal comfort. As for the latter, the spatial system can vary from urban, neighbourhood, to individual building scales. For example, green infrastructure at the urban scale can be built to enhance urban resilience (Pamukcu-Albers et al., 2021). At the neighbourhood scale, designing comfortable public open spaces can enhance people's thermal resilience (Sánchez Ramos et al., 2022; Sharifi et al., 2016). In the field of low-energy buildings, indoor thermal resilience has been emphasized for addressing overheating risks through ventilative cooling (Attia et al., 2021; Tavakoli et al., 2022).

1.2.2 Process of human adaptation to thermal comfort

Climate change and increasing heatwaves also trigger the urgent need for developing strategies for human adaptation to extreme heat (Lam et al., 2019; Li et al., 2023; Lowe et al., 2011). People are not passive recipients of the thermal environment but rather actively create their thermal preferences, according to an adaptive model of comfort, and the adaptive hypothesis of thermal comfort states that “people in warm climate zones prefer warmer indoor temperatures than people living in cold climate zones” (de Dear & Brager, 1998). Based on the fundamental assumption of the adaptive principle, humans adapt to thermal comfort in a condition that ‘if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort’ (Nicol & Humphreys, 2002). The system of human thermal adaptation involves three main procedures in terms of behavioural adaptation, physiological adaptation, and psychological adaptation, stemming from studying the building indoor environments (Brager & de Dear, 1998; Yao et al., 2022). In outdoor thermal comfort studies, more diverse factors would have influences, including the physical factors for the meteorological parameters as well as the sociocultural and economic factors such as age, gender and so on (Lai et al., 2020). This research transition involving a variety of factors calls for a dynamic thermal comfort theory from a human-oriented behavioural perspective (Yao et al., 2022).

1.2.3 Comparative studies of perceived outdoor thermal comfort

It has been found that population characteristics or human factors such as social and cultural backgrounds play an important role in the process of thermal adaptation and cause different thermal comfort perceptions in many comparative studies of perceived outdoor thermal comfort (Aljawabra & Nikolopoulou, 2018; He et al., 2020; Hirashima et al., 2018; Nikolopoulou & Lykoudis, 2006). In addition, the thermal history of people's past thermal experiences can also influence thermal comfort perception (Brager & de Dear, 1998). Thermal history can be characterized as long-term experience (climatic influences on people living for some years) and short-term experience (thermal exposure ranging from weeks to days) (Jowkar et al., 2020). And comparative studies on people with short-term and long-term thermal histories reveal that they may have different expressions of outdoor thermal sensation due to acclimatization (Brychkov et al., 2018; Knez & Thorsson, 2008; Lam et al., 2021). These thermal sensation studies in different climates, cultures, and thermal histories shed light on investigating the effect of heat acclimatization across different climate types.

1.2.4 The effect of heat acclimatization

For exploring the acclimatization of thermal perception, a brief review of similar studies comparing the influence of long-term and short-term thermal history on thermal sensations was summarized (Table 1). These studies investigated the identical climate type of temperate zones, the summer survey periods, and the same outdoor use in urban public open spaces. The topic searching command of '(neutral UTCI) AND (greenspace* OR park* OR square* OR street*)' was applied in the Web of Science Core Collection database on 29 November 2022. Universal Thermal Comfort Index (UTCI) was used to objectively assess the thermal sensation. UTCI is defined as the air temperature of the reference environment, following the concept of an equivalent temperature, and it is one of the thermal indices that show the best predictability of thermal sensation vote (Bröde et al., 2012; Pantavou et al., 2014; Xu et al., 2023). Also, this thermal index has the sensitivity advantage for depicting ambient stimuli changes and temporal variability of thermal conditions (Blazejczyk et al., 2012). And the neutral temperature is commonly used for examining thermal sensation as a benchmark. It indicates no thermal stress in the thermal condition where people neither feel cold nor hot but neutral (Fanger, 1972). Thermal neutrality was first introduced by Humphreys (1975), who found statistical relationships between thermal neutralities and the prevailing temperature in the indoor environment (de Dear & Brager, 1998; Nikolopoulou et al., 2001). Neutral temperature can be an important benchmark for developing strategies to optimize outdoor thermal environments by urban planners (Cheung & Jim, 2017). So, neutral UTCI indicates the UTCI value when people's thermal sensation is neutral rather than hot or cold.

These studies show the effect of heat acclimatization on residents with a long-term thermal history. Lam and Lau (2018) investigated NUTCI in Melbourne and Hong Kong in summer, and they also identified that the Melbourne residents could be less adapted to the extremely hot days because Melbourne summers were mostly cooler and drier than Hong Kong. Xue et al. (2020) also found that occupants living in Shanghai for a longer period such as over 7 years tend to have the highest NUTCI, which means more tolerant to the heat. Lam et al. (2021) also found Guangzhou and Zhuhai residents have higher neutral values of air temperatures than Melbourne because Guangzhou and Zhuhai have higher temperatures in summer than Melbourne. But the NUTCI in Melbourne is higher than in Guangzhou. This might result from the different shading conditions of survey sites, which is the limited shading in Melbourne but the highly shaded in Guangzhou. Thus, acclimatization to the thermal environment has a significant contribution to explaining the discrepancies of the thermal indices among the same population (Xu et al., 2022).

Table 1

The effect of heat acclimatization on NUTCI

Reference	Climate type	City	Site description	Summer survey period	Linear regression equation	NUTCI (when MTSV=0)
Lam and Lau (2018)	Cfb	Melbourne	Greenspaces with trees, and squares with waterways	January-February, 2014	MTSV=0.1047UTCI-2.0257, R^2=0.947	19.3 °C
	Cwa	Hong Kong	Parks and lift-up buildings	July-August, 2007	MTSV=0.0889UTCI-2.0944, R^2=0.8896	23.6 °C
Xue et al. (2020)	Cfa	Shanghai	Greenspaces with lawns, lakeside, trees	May to October 2019	<1 year: MTSV=0.14UTCI-3.07, R^2=0.83 [1, 3 years): MTSV=0.13UTCI-2.77, R^2=0.91 [3,7 years): MTSV=0.14UTCI-3.19, R^2=0.83 >7 years:	<1 year: 21.93°C [1, 3 years):21.31 °C [3,7 years): 22.79°C >7 years:

Reference	Climate type	City	Site description	Summer survey period	Linear regression equation	NUTCI (when MTSV=0)
					MTSV=0.16UTCI-3.69, R^2=0.96	23.06°C
Lam et al. (2021)	Cfb	Melbourne	Greenspaces with trees, and squares with waterways	January-February, 2014	MTSV=0.1081UTCI-2.2021, R^2=0.950	20.37°C
	Cfa	Guangzhou	Squares next to the lift-up building, and street trees	September 2018	MTSV=0.1100UTCI-2.0326, R^2=0.7023	18.48°C
	Cwa	Zhuhai	Squares next to the lift-up building	September 2018	MTSV=0.1315UTCI-3.5313, R^2=0.6888	26.85°C

1.2.5 The hypothesis for thermal resilience

Based on previous studies, the effect of heat acclimatization indicates that people living in a warm climate for a longer time would have higher neutral temperatures, which means enduring more heat stress. And their study sites of public open spaces mainly include greenspaces and squares. Therefore, in the urban regions, a hypothesis for thermal resilience can be formulated that people living in a hot climate for a long period can endure more heat in urban public open spaces during the heatwaves.

1.3 Research gaps and overarching aim

Previous studies have investigated the influence of long-term and short-term thermal history on thermal comfort perception in various outdoor open spaces in different climate types or the same population. However, it is not clear to what extent humans with long-term and short-term experience of hot-summer exposure can adapt to thermal comfort in urban public open spaces when both experience their heatwave periods. Based on the effect of heat acclimatization, this study formulates the hypothesis for thermal resilience that people living in a hot climate for a longer period can endure more heat in urban public open spaces during the heatwaves. Therefore, the overarching aim is to investigate outdoor perceived thermal comfort in urban public open spaces during heatwave periods between two groups of people who have long-term and short-term experience of hot-summer exposure. Specifically, this study involves the following objectives:

- To explore the variations of heatwave meteorological parameters and human thermal sensations in urban public open spaces between two groups of people who have long-term and short-term experience of hot-summer exposure;
- To determine the neutral UTCI in urban public open spaces during heatwaves between these two groups of people; and
- To reveal the behavioural adaption measures of these two groups of people for adapting to perceived outdoor thermal comfort in heatwaves.

This study has the following novelty and originality. Theoretically, it deepens the dynamic theory of human thermal comfort through understanding acclimatization in the situation of an extremely high temperature. This study also provides empirical evidence of thermal adaptation in extreme-high temperature events. Practically, this study would contribute to policymakers making plans and strategies as well as provide public guidance for facing extremely high temperatures and the health alert; and for urban planners and designers as well as landscape architectures it would help to create thermally comfortable open spaces.

2 Methodology

2.1 Comparative case study approach

The comparison logic is through a theoretical replication referring to the process of thermal adaptation, which is from a perspective of human-oriented behavioural sensitivity (Yao et al., 2022). Deducing from the principle, achieving the state of thermal comfort can be explained through an adaptation mechanism, including the dimensions of physiological, physical dimension, psychological, and behavioural adaptation, and it would also be influenced by other human factors such as culture, age, gender and so on.

The thermal environment of urban open spaces would directly connect to the usage of outdoor spaces and conduct outdoor activities (Lai et al., 2019). As for conducting outdoor activities in people's daily life, a public square and a park can represent two important urban public spaces, distinguishing them from usages and daily activities. The square is mainly used as a routine place containing lots of commuting people, while the park is mostly used as a resting place where people visit to relax (Thorsson, Honjo, et al., 2007). Thus, involving the two public spaces with contrasting social functions enables providing a full picture of human adaptation behaviours for each city during heatwave exposures.

The cases can be people with long-term and short-term thermal histories. Thermal history refers to people's past thermal experiences (Brager & de Dear, 1998). They can be characterized as long-term (climatic influences on people living for some years) and short-term (thermal exposure ranging from weeks to days) (Jowkar et al., 2020). Because the prime contextual variable in adaptive thermal comfort is the climate, which has an overarching influence on cultural and thermal attitudes (Nicol & Humphreys, 2002). Besides, two urban open spaces, squares and parks, are selected in each group of people's cities. Overall, four case studies are designed in this study, constituting public squares and parks in two groups of people with different thermal histories of heatwaves. In each case study, the perceived thermal comfort was tested, and the embedded units for analysis were conducted following an analogous logic of three thermal adaptation dimensions (Fig. 1). Because four to six case studies can use a theoretical replication (Yin, 2018). They include the physical factors of climate parameters, the psychological factors of votes for thermal sensation, and thermal adaptation measures that resulted from the human factors for thermal comfort adaptation.

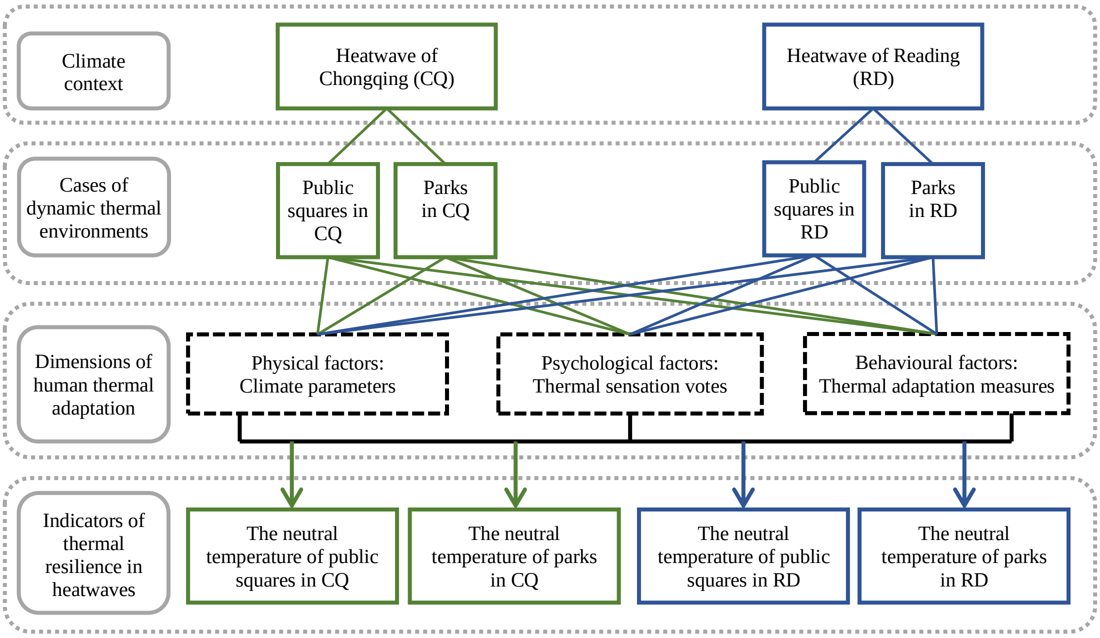


Fig. 1. Comparative case studies design in this study.

2.2 Heatwaves and study sites in Chongqing and Reading

2.2.1 Heatwaves

Heatwave periods are different in the summers of Chongqing (in China) and Reading (in the UK), mainly due to their differences in climate types. According to the Köppen-Geiger climate classification, they are both temperate climates and have no dry season, but the summer in Chongqing is hot while it is warm in Reading (Beck et al., 2018; Kottek et al., 2006). The climate features may cause different criteria for heat alerts in China and the UK. In China, they are mainly based on the day's maximum temperature and duration time, while the alerts in the UK also consider the health impacts on local people. There are three levels of high-temperature warning signals in China. The yellow warning signal is in place when the maximum day temperature reaches over 35 °C in three consecutive days; the orange warning signal indicates that the highest day temperature will rise above 37 °C in 24 hours; and the red warning signal means that the temperature will be over 40 °C in 24 hours. According to the Heatwave Plan for England, there are five levels of the heat-health alert system (UKHSA et al., 2014). Level 0 is long-term planning, and Level 1 is in place every year from 1 June to 15 September for heatwave and summer preparedness. The remaining levels are judged by the maximum temperatures and a 60% chance of high-enough temperatures on 2~3 consecutive days (level 2), threshold temperatures reached in any one region (level 3), as well as the cross-government assessment of the weather conditions (level 4). For levels 2 and 3, the average threshold of maximum day temperatures is 30 °C.

This climatic difference in the summer is ideal for this study to research the heatwave influences on human adaptation to thermal comfort. Chongqing is known as a 'furnace city' (Yao et al., 2018) and people have been living in a hot climate for a long time. On the other hand, Reading unusually experienced a sudden heatwave in 2022. The knowledge of thermal adaptation can be gained by comparing how people can adapt and respond to extreme heat events.

Compared with Reading, heatwave would be more intense and take a longer duration in Chongqing, which already has a hot summer. During the 2020 summer in Chongqing, it experienced high-temperature days with temperatures over 35°C starting in May, and the month of August experienced 28 days of over 35°C (CMS, 2020). Field survey dates in late August (26, 27, and 28) were the three days counted as high-temperature days that all exceed 35°C but below 40°C (Table 2).

Table 2

The recorded High-temperature dates in 2020 at Chongqing Shapingba station

Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
May.	-	-	*	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-
Jun.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*	*	-	-	-	-	-	-	-	-	I	*	-	-	-	-	
Jul.	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	*	*	*	-	*	I	*	-	-
Aug.	*	I	I	I	I	I	I	*	*	I	*	I	*	I	I	I	*	-	-	-	*	*	II	*	*	*	I	I	II	I	*

Notes: Chongqing field survey days are in the dashed frame. ' - ' meaning < 35°C, 35°C ≤ * < 37°C, 37°C ≤ I < 40°C, II ≥ 40°C, and they represent the maximum day temperature. Shapingba station provides temperature data that covers field survey areas. Source: CMS (2020).

While in the Reading cases, the exceptionally high temperatures in the 2022 heatwave period would be shorter and more intense in the middle of the months (Table 3). The record-breaking high temperature was over 40°C, which is comparable to the Chongqing heatwaves. It was reported that on 19 July 2022 temperatures of over 40°C were recorded at several locations across the UK (UKHSA, 2022). Significantly, 40.3°C was recorded at Coningsby (Lincolnshire) marking a heatwave milestone in UK climate history, and for the first time, a Level 4 heatwave alert was also issued by the UK Health Security Agency and the Met Office, which results in the government declaring a national emergency (Kendon, 2022; PressOffice, 2022).

Table 3

Daily highest temperatures (°C) recorded at the Heathrow station and levels of heat-health alerts (in colours) issued for London and South East England in 2022

Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Jun.	19	22	23	22	15	19	22	24	21	25	24	23	22	25	28	29	33	25	20	23	26	28	27	23	22	23	21	23	22	21	
Jul.	22	24	24	23	22	25	25	29	28	30	32	31	29	25	27	29	31	37	40	27	24	23	28	29	25	23	22	25	28	27	28
Aug.	28	27	27	26	23	25	28	30	29	31	33	34	34	33	30	24	24	28	25	26	25	23	27	29	22	25	25	24	23	24	25

Notes: Reading field survey days are in the dashed frames. According to the Heatwave Plan for England, levels of heat-health alerts plan the actions to be taken before and during heatwave periods, instead of temperatures. Colour meanings: Level 1, Level 2, Level 3, and Level 4. Source: MetOffice (2022); UKHSA (2022); UKHSA et al. (2014).

2.2.2 Study sites

In addition to the research significance for the abnormally hot weather, relieving heatwave impacts and improving human-perceived thermal comfort can be important for both Chongqing and Reading. UHI intensity in Chongqing is particularly strong in summer but the cooling capacity of local green spaces and the river is limited due to the densely developed riverside and the high humidity climate (Yao et al., 2015). Reading is not yet officially a “city” but forms the economically vibrant and connected small urban area (Dixon et al., 2018). A comfortable outdoor thermal environment is conducive to outdoor activities, bringing social, health, and environmental benefits (Li et al., 2016). Thus, outdoor thermal comfort for improving the quality of open spaces is also important for vibrant city life and long-term sustainable development in Chongqing and Reading.

Open spaces of liveability and vitality are chosen as study sites since these spaces undertake most outdoor activities, which is an important measure of a pleasurable microclimate experience (Chen & Ng, 2012; Gehl, 2011). In Chongqing, landmark places of parks and squares for entertainment and recreation in the three most flourishing business districts are selected, including Jiefangbei, Guanyinqiao, and Shapingba business districts. In Reading, three central areas representing the most vibrant urban centre and the strategic locations for adapting to the impacts of climate change and addressing climate risks are included. They are the Reading Central Business Improvement District, the Riverside and Meadows area, and the East Reading residential area (RCCP, 2019) as well as a public square in front of the Reading university library. The study site locations in two cities are shown in Fig. 2. In Chongqing, squares contain the sites of I, II, and III, and parks include IV and V. As for Reading, A, B, and C sites are functioning as a square, and D, E, F, and G are used as parks.

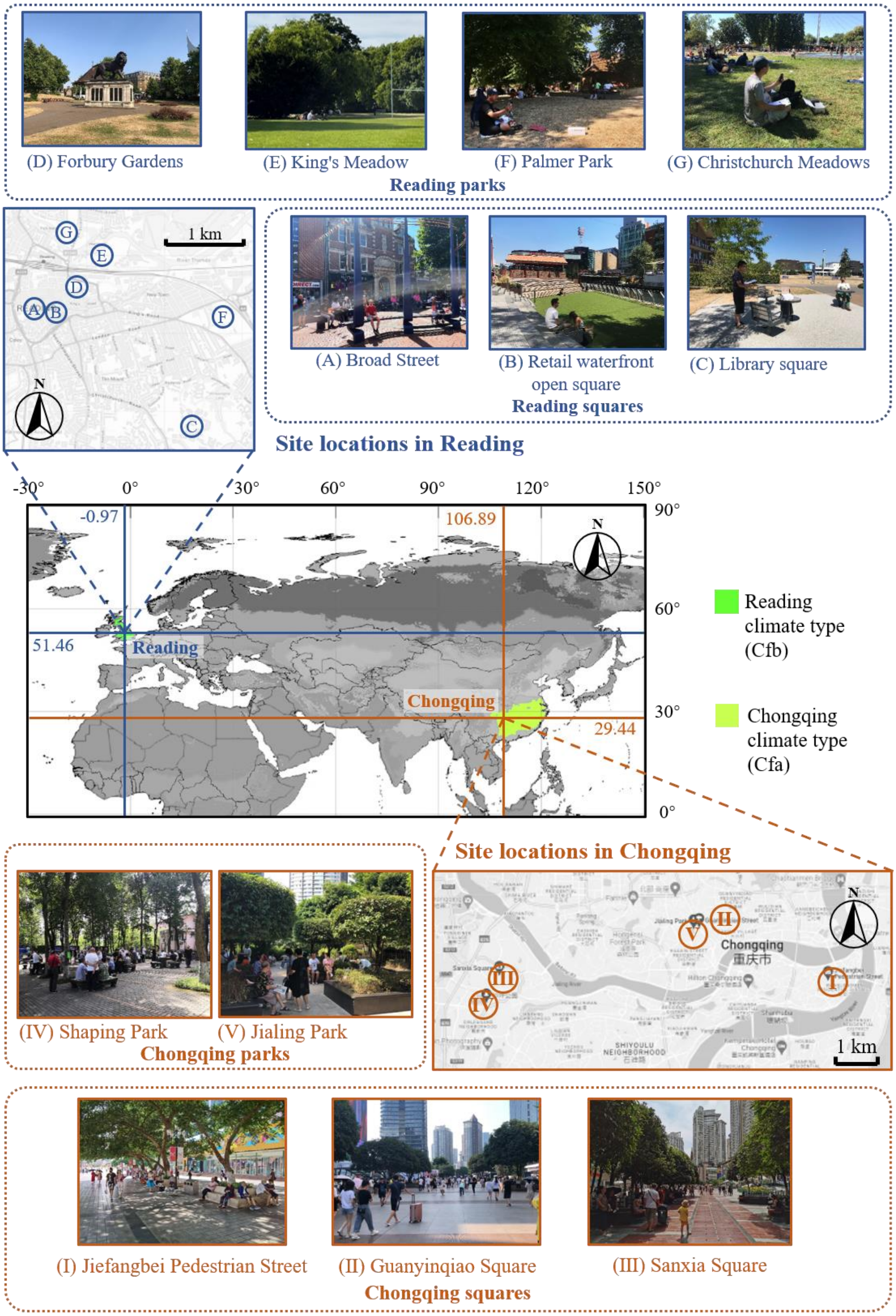


Fig. 2. Study site locations and configurations in Reading climate (Cfb) and Chongqing climate (Cfa) categorized by the Köppen-Geiger climate classification shown in the present-day map (1980–2016). Figure sources: Climate classification world map

(https://www.nature.com/articles/s41597-020-00616-w/figures/1), Reading map (Digimap), Chongqing map (Google Maps), and onsite photos are authors' own.

2.3 Field survey

2.3.1 Field microclimate measurement

Measurement campaigns were conducted during the heatwave periods of Reading and Chongqing in the study sites. Microscale climate observations were conducted at a distance of 100m for each study site (WMO, 2008). Meteorological parameters including air temperature (T_a), relative humidity (RH), wind speed (V_a), and globe temperature (T_g) were measured for estimating human heat stress (Bröde et al., 2012; Jendritzky et al., 2012). Table 4 lists the instruments. The height of measurement corresponds to the height of the centre of gravity for humans (Mayer & Höppe, 1987), and it was around 1-1.1m above ground when sitting or standing which are typical activities happening during the survey. Global radiation was measured by a tailored-made globe thermometer consisting of a robust air temperature probe with an exposed sensor (thermocouple type K) held in the middle of a black globe enabling to measure the global radiation with a short response time referencing previous studies (Johansson et al., 2014; Ng & Cheng, 2012; Nikolopoulou et al., 1999). The meteorological parameters were recorded once per 10 minutes in each location. Then each respondent based on the time of filling out the questionnaire was assigned the meteorological parameters for calculating the thermal index. Heatwave survey dates in Reading include 17 July and 09-13 August 2022, and Chongqing heatwave periods cover from 26 to 28 August 2020.

Table 4

Measured meteorological parameters and instruments

Meteorological parameter (units)	City	Instrument	Range	Accuracy
Air temperature (°C)	Reading	Kestrel 4000	-29.0 to 70.0°C	±1.0°C
	Chongqing	Onset Hobo, UX100-011A	-20 to 70°C	±0.21°C

Meteorological parameter (units)	City	Instrument	Range	Accuracy
Relative humidity (%)	Reading	Kestrel 4000	0.0 to 100.0%	±3.0%
	Chongqing	Onset Hobo, UX100-011A	1 to 95%	±2.0%
Wind speed (m/s)	Reading	Kestrel 4000	0.4 to 40.0m/s	±0.1m/s
	Chongqing	WWFWZY-1	0.05 to 30 m/s	±0.05m/s
Globe temperature (°C)	Reading	Testo 435-4	-50 to +150°C	±0.2°C
	Chongqing	HQZY-1	-20 to 80°C	±0.3°C

2.3.2 Self-completion questionnaire

Pedestrians were selected based on random sampling in the locations and they were interviewed once during the survey period, the same as other thermal perception studies using a transverse approach to sampling (Potchter et al., 2022). People with relatively quiet activities such as reclining, seated, standing, and strolling were interviewed. Because for outdoor activities, recreational and social activities, such as sitting, stopping, or standing around enjoying life, would indicate a higher quality of the physical environment that favours people staying outdoors (Gehl, 2011). Participants were interviewed for their thermal sensations, thermal adaptation behaviours to improve outdoor thermal comfort, clothing, and demographic information (i.e. gender, height, weight, and age). The question for thermal adaptation behaviours asks "What would you usually do to improve outdoor thermal comfort in summer? (Please tick all that apply)" and it has multiple choices of measures, including moving to cool spaces, moving to ventilated spaces, using umbrellas, using portable fans, taking cold drinks, decreasing activity intensity, wearing hats, decreasing clothes, and if other please specify. The clothing insulation values were extracted from ASHRAE Standard 55-2017 (ASHRAE, 2017). The questionnaire language was presented in English in Reading and Chinese in Chongqing, and the two questionnaires have been checked by professionals for conveying the same meaning. Research ethics for the human subject study protocols in the two cities were both consent and approved by supervisors, following the administrative process of the two universities.

2.3.3 Determining sample sizes in the survey

In this study, a 90% confidence level and a 5% margin error were adopted (Canan et al., 2019). The required sample size for surveying the two cities was calculated using the following equation (1) (Krejcie & Morgan, 1970):

$$s = x^2NP(1-P) \div d^2(N-1) + x^2P(1-P) \quad (1)$$

Where:

s is the required sample size;

x^2 is the table value of chi-square for 1 degree of freedom for the desired confidence level;

N is the population size;

P is the population proportion (it can be assumed to be 0.50 allowing for the maximum sample size);

d is the desired margin error (expressed as a proportion).

There are 161,780 residents (ONS mid-year estimates 2019) living within the Reading borough boundary (ONS, 2019). As for the population of Chongqing, the urban resident population is 20,869,900 in 2019 (CMBS, 2020). Thus, the sample size representative is 273 for both Reading and Chongqing. In this study, there are 325 respondents in Reading and 789 in Chongqing, which is enough for representing the population.

2.4 Statistical analysis

2.4.1 Mann-Whitney U Test for comparing the Thermal Sensation Votes (TSVs)

The Mann-Whitney U Test is used to analyse if there are differences in TSVs between the squares group and the parks group. This test compares the medians of TSV ranks across the two groups. Because TSVs were measured on the ordinal category rating scale including very hot, hot, warm, neutral, cool, cold, and very cold.

2.4.2 Universal Thermal Comfort Index (UTCI) calculation

In this study, Universal Thermal Climate Index (UTCI) is adopted for assessing human thermal comfort for capturing intense variations of climate conditions in heatwaves. The input parameters include the measured ones: T_a and RH, as well as ΔT_{mrt} and the wind speed at 10m height, as required from the UTCI website (http://www.utci.org) (Eq. 2). Mean radiation temperature (T_{mrt}) is estimated by the following equation 3 (ISO., 1998; Thorsson, Lindberg, et al., 2007).

$$UTCI = f(T_a, RH, \Delta T_{mrt}, v_x) \quad (2)$$

where $\Delta T_{mrt} = T_{mrt} - T_a$.

$$T_{mrt} = [(T_g + 273)^4 + \frac{1.1\times 10^8 \times V_a^{0.6}}{\varepsilon D^{0.4}}(T_g - T_a)]^{\frac{1}{4}} - 273 \quad (3)$$

where D is the globe diameter (0.04m for Reading and 0.15m for Chongqing) and ε is the emissivity (0.95 for a black globe).

UTCI requires wind speed at 10m above the ground level, but it is rare to be able to measure during a field survey campaign (Bröde et al., 2012; Cheung & Jim, 2018). A logarithmic wind profile approach, the following equation 4, was adopted to calculate the wind speed at 10m (v_{10}) height above ground (Havenith et al., 2012).

$$v_x = v_m \times \frac{log\left(\frac{x}{z_0}\right)}{log\left(\frac{m}{z_0}\right)} \quad (4)$$

where x (m) is 10m, z_0 (m) is the roughness length (0.01m for a short-cut meadow or an urban street environment), $and\ m$ (m) is the measurement height of wind speed (1.5m in this study's measurement).

2.4.3 Linear regression for determining the Neutral UTCI (NUTCI)

To determine the neutral temperatures for the two cities, this study uses the linear regression between the Mean Thermal Sensation Vote (MTSV) and the UTCI values, which is one of the most common methods (Potchter et al., 2022). Similar to numerous other researchers, MTSV was averaged for every 1°C UTCI interval for reducing the individual differences in each city (Lin & Matzarakis, 2008). Although the linear regression method is sceptical by Cheung and Jim (2017) for treating the TSV as a continuous variable, this impact has been found insignificant (Kenawy & Elkadi, 2018).

2.4.4 Determining sample sizes for Mean TSVs (MTSVs)

The appropriate sample size for MTSV as a continuous variable can be determined using Cochran's sample size formula for continuous data (Eq. 5) (Kotrlik & Higgins, 2001):

$$n_0 = \frac{(t)^2 \times (s)^2}{(d)^2} \quad (5)$$

where:

n_0 is the required return sample size;

t is the value for the selected alpha level (1.65 for a 90% confidence level in this study);

s is the estimate of standard deviation in the population [for a 7-point scale of thermal sensation votes in this study, it is calculated by using 7 divided by 6 (number of standard deviations that include approximately 98% of the possible values in the range) and equals to 1.167];

d is the acceptable margin error for the mean being estimated (equals to points on the primary scale multiplied by the acceptable margin error, and 7*5%=0.35 in this study).

Through the procedure, the minimum returned sample size for a seven-point scale of thermal sensation votes should be 30. All techniques for statistical analysis were conducted in IBM SPSS Statistics 26.

3 Results and analysis

3.1 Thermal adaptation in Chongqing

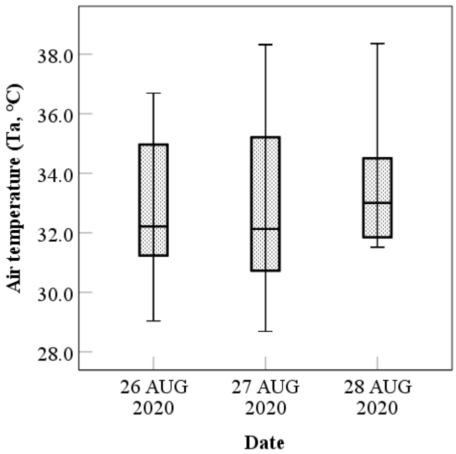
3.1.1 Biometeorological profile

A total number of 789 were collected in Chongqing (Table 5), and this exceeds the required sample size of 273 for representing the population of each city, as calculated in section 2.3.3. Specifically, there were more male respondents and the age groups of respondents were mostly 16-25. Body Mass Index (BMI=Weight/Height^2) was used for revealing the obesity level of respondents (Prentice & Jebb, 2001). The average BMI is 22.9 kg/m². And the average clothing insulation is 0.3clo.

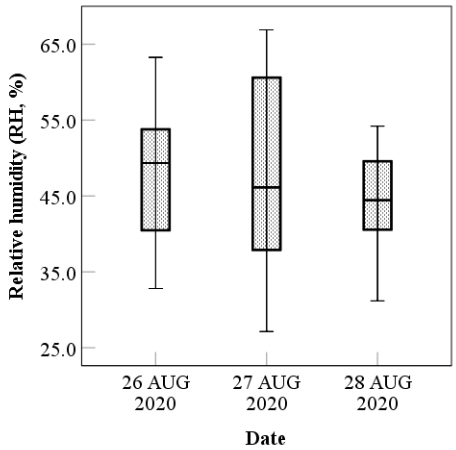
Table 5 Respondents' characteristics in Chongqing

Chongqing respondent number					Major age group	BMI (kg/m²)			Clothing insulation (clo)		
Total	Public open spaces		Gender			MAX	MIN	AVG	MAX	MIN	AVG
789	Squares	666	Male	482	16-25	55.6	12.2	22.9	0.7	0.1	0.3
	Parks	123	Female	307							

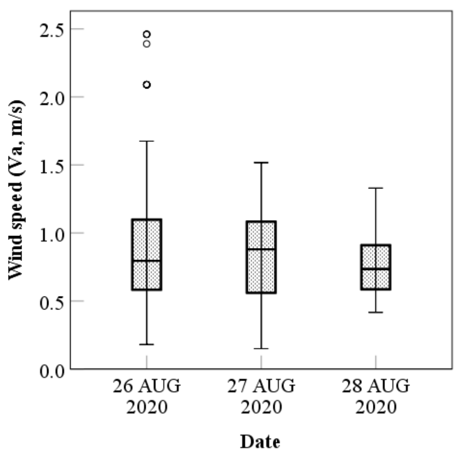
The main T_a distribution would hover around 31 to 35°C in Chongqing (Fig. 3a). The RH is generally higher than 40% (Fig. 3b). The main V_a values are below 1.5m/s (Fig. 3c). In Chongqing only respondents in the shaded areas were interviewed, and the general distribution of T_g is 31~36°C (Fig. 3d).



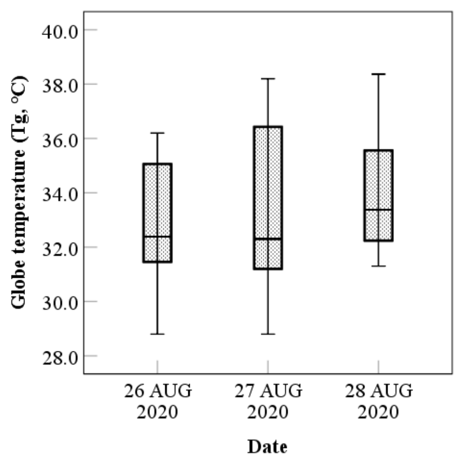
(a) T_a



(b) RH



(c) V_a



(d) T_g

Fig. 3. Field-measured meteorological parameters in Chongqing including T_a (a), RH (b), V_a (c), and T_g (d).

3.1.2 Thermal sensation votes

It is shown that the warm sensation was voted most in the squares and the parks in Chongqing (Fig. 4). Based on the statistical analysis, the Mann-Whitney U Test reveals a significant difference (the Sig. value is 0.029, less than 0.05) in TSVs among respondents. In this test, the total respondent number is 789, U=36088, z=-2.184, p=0.001, r (effect size = z/√N) =0.08 (a small effect size). Their medians of TSV are both 1 meaning warm. As for the sensation difference, the square group (N=666, mean rank=402.31) is higher than the park group (N=123, mean rank=355.40).

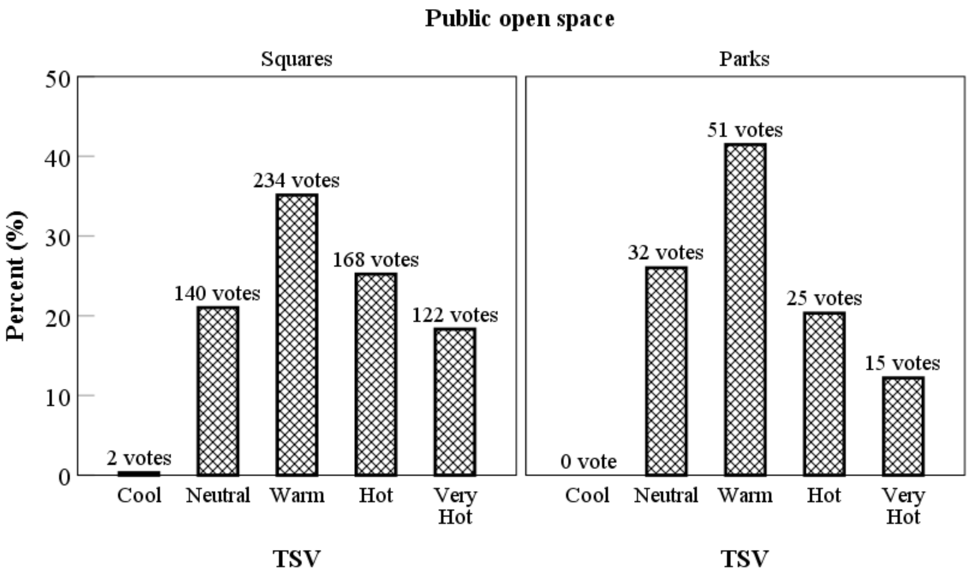


Fig. 4. TSVs distributions in squares and parks in Chongqing. (For coding TSV: Very hot=3, Hot=2, Warm=1, Neutral=0, -Cool=-1; the other two points were not voted under the heatwave research circumstances, so only voted points are displayed.)

3.1.3 Thermal adaptation measures

- *Changing places and activities*

Moving to cool spaces is a main measure to adapt to outdoor thermal comfort, with about

80% in parks and 70% in squares respondents in Chongqing (Fig. 5). Moving to ventilated spaces is a less popular measure, and approximately 40%-50% of respondents would take this. On the other hand, decreasing activities is one of the least measures in Chongqing.

- *Taking cold drinks*

Taking cold drinks is a less popular choice among Chongqing respondents. And around 30%~40% of respondents would prefer to take cold drinks.

- *Decreasing clothes*

Decreasing clothes is another least favourable measure in Chongqing. Besides, it is surveyed that the clothing insulation values in both the squares and the parks were higher than 0.30clo. (Fig. 6). The parks have a higher median of clothing insulation with 0.35clo.

- *Other individual measures*

Using portable fans is a relatively popular measure nearly 30% in Chongqing, and it is more popular in the parks with over 50%. The next is using umbrellas with over 20% of respondents. Wearing hats is one of the least choices with less than 20% of respondents.

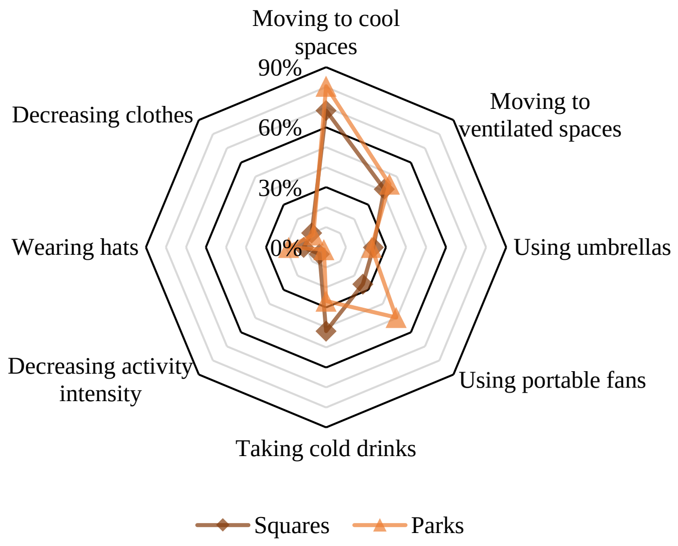


Fig. 5. Thermal adaptation measures for thermal comfort in Chongqing

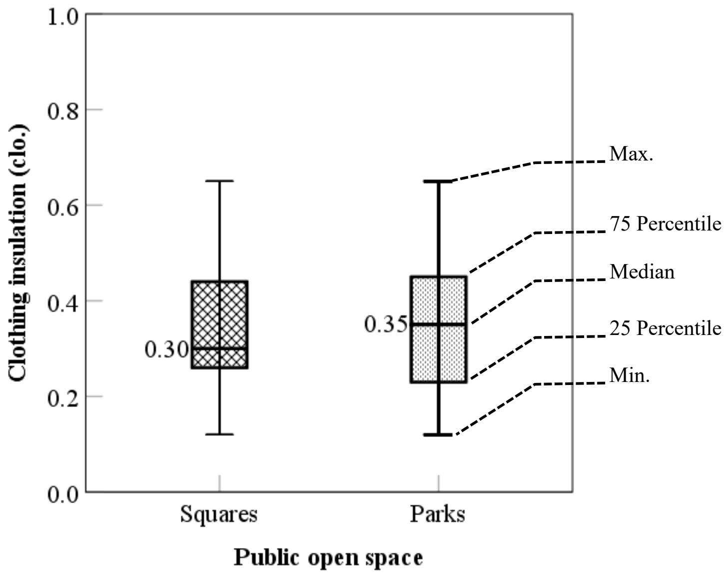


Fig. 6. Clothing insulation in squares and parks in Chongqing

3.2 Thermal adaptations in Reading

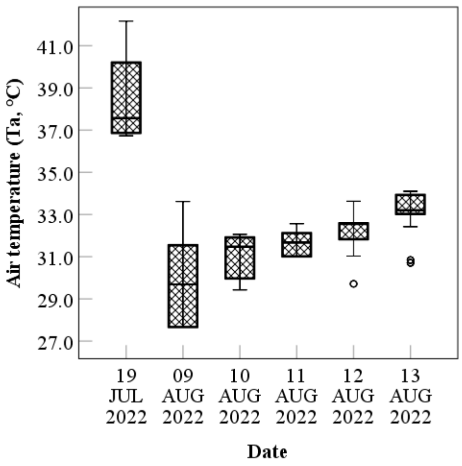
3.2.1 Biometeorological profile

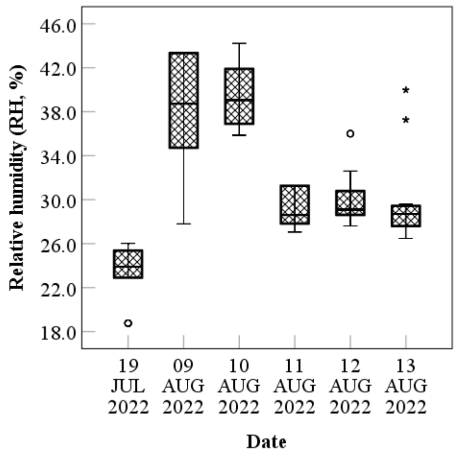
There were 325 respondents in Reading (Table 6). Among them, 158 questionnaires were on the squares and 167 in the parks. And they also exceed the required sample sizes. Reading has more female respondents. The average BMI is slightly higher than that in Chongqing. The major age group is the same as 16-25, and the average clothing insulation is 0.3clo. as well.

Table 6 Respondents' characteristics in Reading

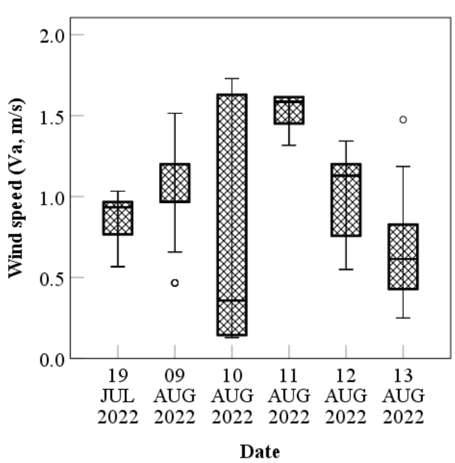
Reading respondent number					Major age group	BMI (kg/m²)			Clothing insulation (clo)		
Total	Public open spaces		Gender			MAX	MIN	AVG	MAX	MIN	AVG
325	Squares	158	Male	133	16-25	57.4	13.6	23.6	0.9	0.1	0.3
	Parks	167	Female	192							

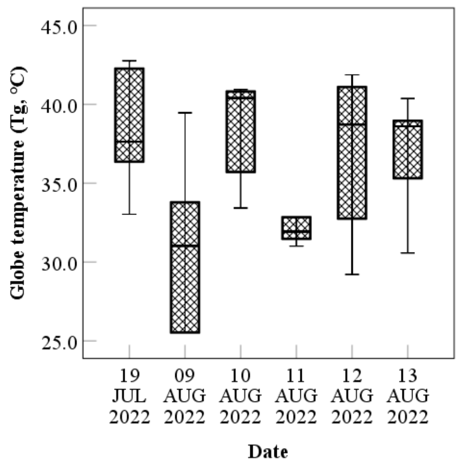
As for the meteorological parameters in Reading, the highest distribution of T_a occurred on 19 July 2022 with over 37°C, and the rest of T_a would hover around 27 to 34°C (Fig. 7a). The RH in Reading is mainly below 42%, generally lower than that in Chongqing (Fig. 7b). And the main V_a values are below 1.5m/s as well (Fig. 7c). The major distribution of T_g ranges from 25 to over 40°C (Fig. 7d) because the respondents in both shaded and sunlit areas were interviewed.





(a) T_a (b) RH





(c) V_a (d) T_g

Fig. 7. Field-measured meteorological parameters in Reading including T_a (a), RH (b), V_a (c), and T_g (d).

3.2.2 Thermal sensation votes

Over half of the respondents voted for 'hot' and 'very hot' in both the squares and the parks in Reading (Fig. 8). And the Mann-Whitney U Test shows no significant difference (the Sig. value is 0.480, higher than 0.05) between the votes in squares and parks. The total number of public open spaces is 325, U = 13758.5, z = 0.706, p = 0.480, r = 0.04 (a very small effect size). The medians of TSVs are both 2 (meaning hot). However, the parks have a higher mean rank

(N = 167, mean rank = 166.39) than the squares (N = 158, mean rank = 159.42). This indicates that most respondents perceived hotter sensations in the parks.

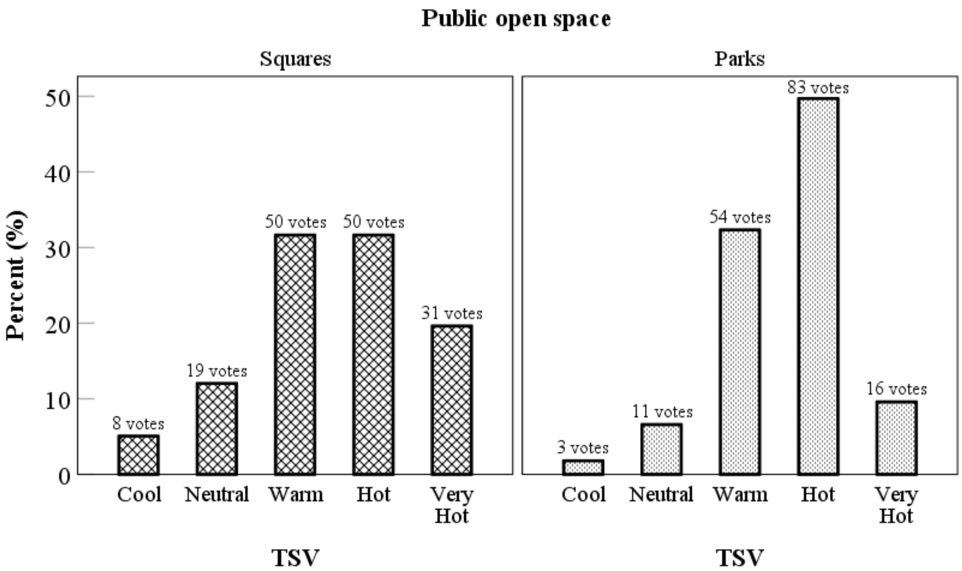


Fig. 8. TSVs distributions in squares and parks in Reading. (For coding TSV: Very hot=3, Hot=2, Warm=1, Neutral=0, -Cool=-1; the other two points were not voted under the heatwave research circumstances, so only voted points are displayed.)

3.2.3 Thermal adaptation measures

- *Changing places and activities*

Moving to cool spaces is a major measure for Reading respondents to improve outdoor thermal comfort in the summer (Fig. 9). Nearly 90% of respondents in parks and squares would choose this. Moving to ventilated spaces is a less popular measure with approximately 40%-50% of respondents. Decreasing activity intensity is another measure that just over 30% of respondents would use this way in Reading. Additionally, a few respondents proposed other measures related to changing places that may not be cool during the survey in Reading. For example, water activities include swimming and being by the sea.

- *Taking cold drinks*

Taking cold drinks in summer is another favourable measure in Reading compared with Chongqing. Nearly 80%-90% of respondents in Reading would consume cold drinks to improve outdoor thermal comfort, such as ice cream and use a cooler for keeping drinks cold.

- *Decreasing clothes*

As for decreasing clothes for thermal adaptation, more than half of Reading respondents (around 60%) would choose to decrease clothes, compared with about 10% of respondents in Chongqing. Besides, in Reading respondents in the parks generally have a lower distribution of clothing insulation than that in the squares (Fig. 10). And the median of clothing insulation in parks and squares is 0.25clo and 0.31clo respectively.

- *Other individual measures*

During the heatwave periods, other measures would be taken by the individual to protect themselves from sunlight exposure in terms of using umbrellas, using portable (electric) fans, and wearing hats. Wearing hats is the relatively prevalent choice (around 30% to 40% of respondents) in Reading, compared with the other two individual measures. Using portable fans would be adopted by less than 30% of respondents. And using umbrellas is the least preferable choice in both parks and squares (below 20%).

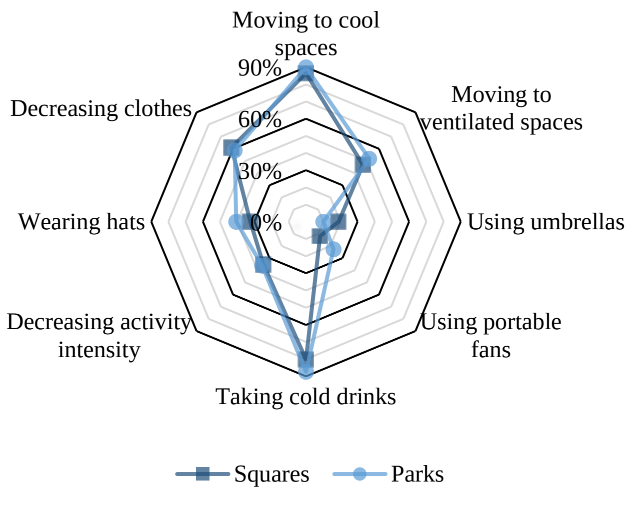


Fig. 9. Thermal adaptation measures for thermal comfort in Reading

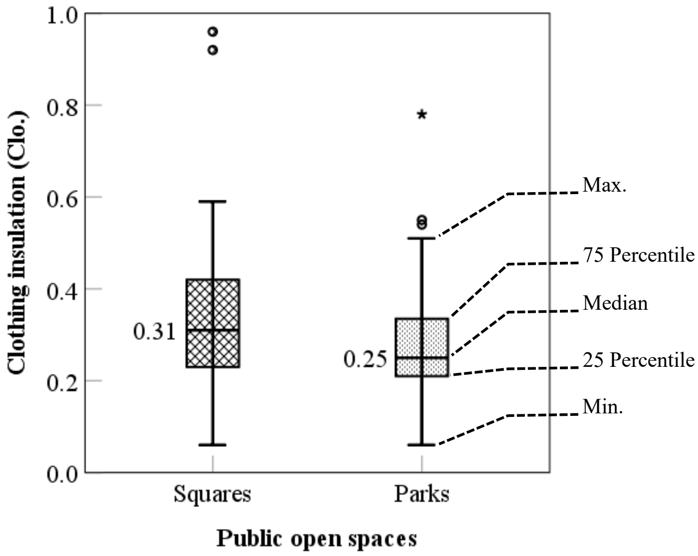


Fig. 10. Clothing insulation in squares and parks in Reading

3.3 Thermal resilience

3.3.1 In Chongqing cases

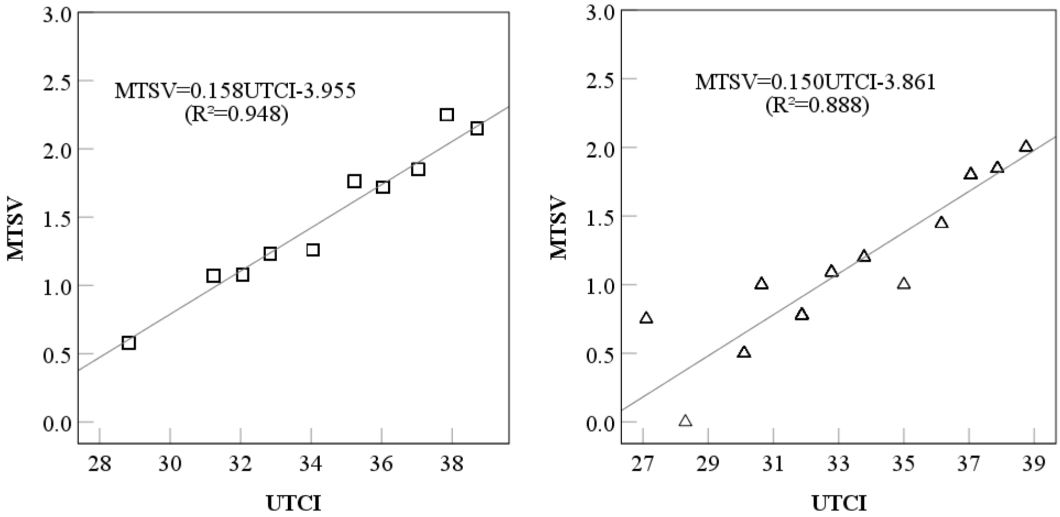
After the linear regression analysis between the MTSV and the UTCI values, the sample sizes in squares and parks for neutral temperatures are over 100 (Table 7). They both exceed the appropriate sample size of 30 for MTSV as calculated in section 2.4.4.

In Chongqing, people in the parks had more thermal resilience than in the squares. When MTSV=0, the NUTCI is 25.74℃ for the parks and 25.03℃ for the squares. On the other hand, a wider range of neutral temperatures can be thermally comfortable in the parks. This can tell from the slope of the fitted line that the parks (Fig. 11b) have a slightly lower slope than the squares (Fig. 11a). The slope value of parks (0.150) corresponds to 6.67℃ UTCI per sensation, while it is 6.33℃ UTCI per sensation in squares. More precisely, the NUTCI range can be calculated when MTSV is between -0.5 and 0.5 (He et al., 2020). The NUTCI range is 22.41~29.07℃ in the parks and 21.87~28.20℃ in the squares.

Table 7 NUTCI results in squares and parks in Chongqing

Public open space	Sample size	Linear regression equation	NUTCI (℃, when MTSV=0)	NUTCI range (℃, when MTSV=±0.5)

Squares	664	MTSV=0.158UTCI-3.955 (R^2=0.948)	25.03	21.87~28.20
Parks	123	MTSV=0.150UTCI-3.861 (R^2=0.888)	25.74	22.41~29.07



(a) Squares (b) Parks

Fig. 11. Correlation between MTSV and UTCI in (a) squares and (b) parks of Chongqing

3.3.2 In Reading cases

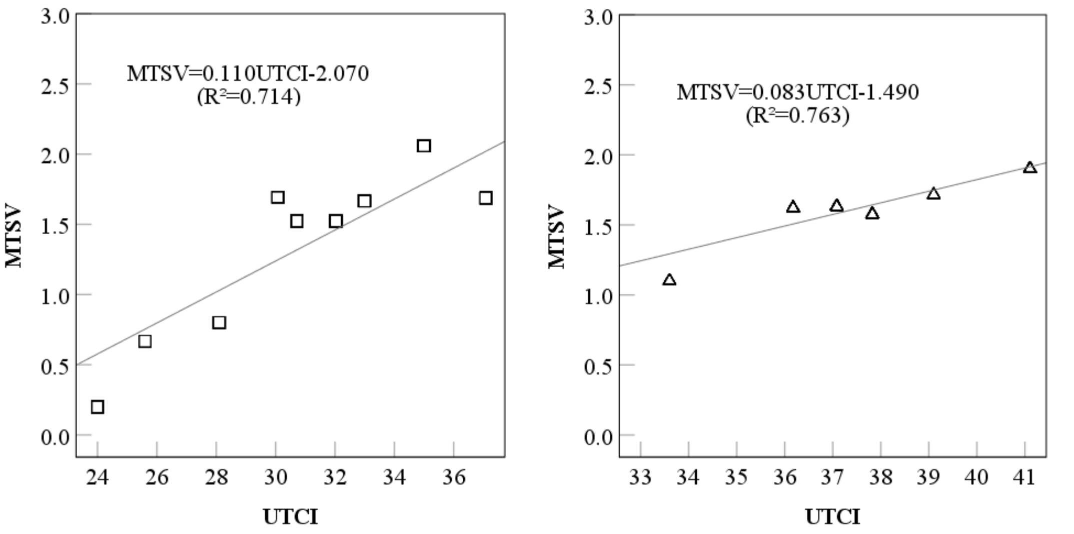
After the linear regression analysis between the MTSV and the UTCI values, the sample sizes in squares and parks for neutral temperatures are over 100 in Reading (Table 8). They also both exceed the appropriate sample size of 30 for MTSV as calculated in section 2.4.3.

By comparing NUTCI values between squares and parks, they had different thermal resilience in Reading. In the squares (Fig. 12a), when MTSV=0, the value of NUTCI is 18.82℃. As for the parks (Fig. 12b), the neutral temperature is 17.95℃. This indicates that people in the squares had more capacity for thermal resilience than the parks in Reading.

Also, a wider range of the neutral temperature in the parks can be thermally comfortable for Reading respondents. And the slope value of parks (0.083) corresponds to 12.05℃ UTCI per sensation, while it is 9.09℃ UTCI per sensation in squares (0.110). The NUTCI range is 11.93~23.98℃ in the parks and 14.27~23.36℃ in the squares.

Table 8 NUTCI results in squares and parks in Reading

Public open space	Sample size	Linear regression equation	NUTCI (°C, when MTSV=0)	NUTCI range (°C, when MTSV=±0.5)
Squares	132	MTSV=0.110UTCI-2.070 (R^2=0.714)	18.82	14.27~23.36
Parks	144	MTSV=0.083UTCI-1.490 (R^2=0.763)	17.95	11.93~23.98



(a) Squares (b) Parks

Fig. 12. Correlation between MTSV and UTCI in (a) squares and (b) parks of Reading

4 Discussion

4.1 Behavioural adaptation

4.1.1 Similarities

The choices of adaptive behaviours can have various consequences for thermal sensations. In the research paradigm of thermal comfort in a human-oriented view, behavioural sensitivity can contribute to developing the dynamic thermal comfort theory (Yao et al., 2022). Therefore, through understanding and comparing the adaptive behaviours in the beginning, the causes for the thermal resilience of Chongqing and Reading respondents can be revealed.

In both cities, thermal adaptation measures have similarities in moving to cool and ventilated spaces. Moving to ventilated spaces constitutes similar percentages in squares and parks, but moving to cool spaces would be the favourite measure for them. Besides, places that may not be cool for water activities such as swimming and being by the sea were added by some respondents. Studies show that beach users can adapt to and even prefer warmer thermal conditions compared to urban users (Arabadzhyan et al., 2021; Rutty & Scott, 2015).

4.1.2 Differences

The main different behaviours for adapting to thermal comfort between the two cities are decreasing clothes and activity intensity as well as some individual measures.

Compared with Chongqing respondents, the Reading respondents have lower median values of clothing insulation in both squares and parks during the heatwave periods. As for squares, the clothing insulation is similar for Reading and Chongqing respondents. In parks, Chongqing participants have generally higher median values of clothing insulation. On the contrary, in the parks of Reading, decreasing clothes and activity intensity, such as reclining and seated was observed during the heatwave survey periods.

The less wearing in parks may be attributed to the activities due to the climatic and cultural differences between northern Europe and eastern Asia. In sunny weather, sunbathing is a frequently occurring activity in Scandinavia, while it is a rare activity in Asia (Thorsson et al., 2004). On the other side, from the results of the thermal index, the difference in cloth choices suggests that Chongqing participants get used to the hot weather and can be more tolerant to heat.

In terms of individual measures, taking cold drinks is the most preferable choice for Reading participants, while this is a less popular measure for Chongqing respondents to improve outdoor thermal comfort. The measure of consuming cold drinks might be linked to cultural differences (Aljawabra & Nikolopoulou, 2018). Using umbrellas is also found in other studies on the Asian population as a choice for improving outdoor thermal comfort (Lin, 2009; Tung et al., 2014) or protecting from sun exposure (Cheng et al., 2010; Yan et al., 2015). Due to the cultural difference in the perception of ideal beauty, in northern Europe, it includes a suntan for most people whereas fair skin is generally preferred in Asia, and also the climatic difference in short and lush summers in Scandinavia, which is why most northern European people automatically choose a place in the sun but in Asia, the majority of people tend to avoid the sun exposure (Thorsson, Honjo, et al., 2007).

As for the thermal adaptation measures such as using fans and wearing hats, participants in parks have larger numbers than in squares in both cities. The noticeable differences are that Reading respondents would prefer to wear hats, but using portable (electric) fans would be more likely chosen by the Chongqing respondents in parks.

4.2 Thermal resilience of respondents

This study finds that Chongqing people living in long periods of hot climates are more tolerant to the heat when a heatwave strikes, suggesting thermal resilience to high temperatures. The thermal conditions where people feel neither warm nor cool but neutral can be measured by the neutral temperature. A higher neutral temperature suggests a higher tolerance level for high temperatures. As an indicator of thermal resilience, the NUTCI values in the Chongqing group (about 25°C) are both higher than the Reading group (around 18°C). Thus, participants of Reading show less tolerance to the hot climate, and Chongqing participants are more adaptable to the hot temperatures.

This dynamic change in thermal resilience confirms an adaptive procedure for achieving human thermal comfort facing extremely high temperatures. This thermal resilience of higher expectation attributes to people with a long-term thermal history background, formed in long-term exposure to a microclimate (Lam et al., 2021). On the other hand, from the perspective of the heatwave event impacts on individual daily life, the cities that experienced the extremely hot weather would be more likely to adapt to the heatwaves and show less sensitivity to the heatwave events on social media (Wang et al., 2021). Thus, habituation in the psychological dimension of thermal adaptation happens (de Dear & Brager, 1998). This factor is even more powerful than heat adjustment for heat tolerance and enhancing thermal resilience.

4.3 Thermal resilience in squares and parks

Urban squares and parks in Chongqing and Reading show different effects for making people feel thermally neutral. The NUTCI for squares (25.03℃) is lower than parks (25.74℃) in Chongqing, while they are on the contrary in Reading (18.82℃ in squares and 17.95℃ in parks). The reason can be that their preferred behaviours are different for sun exposure.

In Reading, activities about less wearing in parks such as sunbathing and choosing a place in the sun would be more likely to happen, as discussed in section 4.1.2. Based on the field survey results in Reading, the median value and the main distribution of clothing insulation were generally lower in the parks than in the squares, as shown in Fig. 10. These sun-exposure activities will make people feel hotter and vote for higher thermal sensations, resulting in a lower value of neutral temperature. Thus, in Reading there was a lower value of neutral temperature in parks than in squares.

On the other hand, Chongqing respondents preferred staying in the shaded areas and thus were interviewed, and the higher value of NUTCI in parks suggests that people in parks could have a higher thermal resilience than squares. This corresponds to the cooling efficiency provided by enhancing urban greenery (Berardi et al., 2020; Gunawardena et al., 2017).

4.4 Limitations and strengths

This study has the limitation of controlling subjects' characteristics due to the random sampling method in the field survey strategy. Random sampling has the advantage of representing the whole population of a place, but its disadvantage is controlling subjects' individual factors such as gender, ethnicity, clothing, and age (Potchter et al., 2022). In this study, the general distribution of clothing insulation for Chongqing respondents is higher than for Reading. Based on the evaluation of the thermal index, more clothes among the Chongqing population may suggest again a higher tolerance level to the heat in the long-term exposure to hot summers.

Additionally, some studies assert that the slope of the fitted line can indicate the thermal sensitivity to the calculated index (Hwang & Lin, 2007). The higher slope would correspond to a higher thermal sensitivity, implying lower thermal adaptability. However, this implication cannot be applied to this study's conditions, because the respondents in two cities were surveyed in different situations of sun exposure. This can result in different radiant heat that influences thermal sensation and the slope of the fitted line. Chongqing respondents were surveyed in the shaded areas and Reading respondents were surveyed in both shaded and sunlit areas, resulting in a lower slope of Reading respondents compared with Chongqing. But because of this, the sunlit behaviours in Reading's parks can be revealed, proved by the lower NUTCI value of the parks than its squares. On the other hand, this difference also indicates that if people are willing to stay in the shaded areas, the parks would be a better place than the squares to improve their thermal comfort.

Finally, the understanding of human thermal adaptation could be improved, if the full picture of heatwaves would be covered in the field survey. To achieve this, the monitoring technology for heatwave forecast needs to be more accurate and realistic in future research.

5 Conclusions

This study investigates the extent to which humans with long-term (in Chongqing) and short-term (in Reading) experience of hot-summer exposure can adapt to thermal comfort in urban public open spaces when both experience their heatwave periods. The two cities have different summer climates. Chongqing is known as a 'furnace city' and people have been living in a hot summer for a long time, while in Reading the summer is warm and people unusually experience the heatwave. In addition, creating thermally comfortable open spaces is conducive to outdoor activities bringing social, health, and environmental benefits, which is important for vibrant city life and long-term sustainable development for both cities. These qualifications of summer climates and city development goals are ideal for this study to research heatwave influences on thermal resilience in Reading and Chongqing.

Field surveys were conducted during the late period of heatwaves in terms of July and August 2022 for Reading and August 2020 for Chongqing. Questionnaires about thermal sensation votes and thermal adaptation behaviours along with meteorological parameters were collected. NUTCI values for respondents, as well as parks and squares in two cities, were determined. Finally, different responses and choices of thermal adaptation to extreme heat events were found in Chongqing and Reading. The main conclusions can be drawn as the followings:

1) Compared with Reading respondents facing heatwaves, Chongqing respondents under long-term exposure to high temperatures show a higher level of tolerance to the heat. This implies that the residents living in a hot climate for a long period have climatization and gain more capacity for thermal stress during heatwaves. The adaptive sign might also suggest that heatwaves would cause fewer health risks when already accustomed to high temperatures. This indicates that protective measures against heatwaves should be taken by urban planners and designers, especially for Reading residents that do not yet face long-term high temperatures.
2) From the perspective of behavioural adaptation to thermal comfort, people are active participants to choose their thermal preferences, rather than passive recipients of the thermal environments. Moving to a cool and ventilated space is a common preferable choice for both Reading and Chongqing participants. As for the behaviour differences, Chongqing respondents would prefer to use umbrellas and portable (and/or electric) fans, while taking cold drinks and wearing hats were more popular among Reading participants.
3) As for thermal resilience in public squares and parks, the values of NUTCI show an opposite trend in the two cities. In Chongqing, it is higher in parks than in squares, but it is lower in Reading's parks than in its squares. Thus, the respondents from Chongqing's parks have more tolerance to the hot weather compared with Reading's parks. The temperature differences may be attributed to the preferred behaviours in parks due to different cultures for experiencing sun exposure between the two cities. In the summer in Chongqing, people tend to avoid sun exposure. While in Reading's parks, activities about less wearing and choosing a place in the sun such as sunbathing would be more likely to happen, resulting in higher votes for thermal sensation and consequently the lower values

of the NUTCI.

For enhancing thermal resilience, behavioural adjustments offer the greatest opportunities. In adapting to extreme heat events, behaviours such as taking cold drinks, using portable fans, using umbrellas, and wearing hats for avoiding sun exposure can greatly improve the perceived thermal comfort while conducting outdoor activities. Additionally, urban planners and designers need to provide more shaded places with efficient ventilation designs, such as trees, lift-up or semi-closure building designs and covered winding corridors for sheltering. And handy facilities such as drinking fountains and water spray need to be offered to better meet pedestrians' requirements for thermal adaptation and help to enhance thermal resilience.

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