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Heat resilience in public space and its applications in healthy and low carbon cities

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Abstract

Australian cities are experiencing more heat stress in the 21st century than ever before. Public life in a majority of Australian cities suffer from heat stress in urban heat islands. This paper presents the concept of spatial heat resilience as the capability of the built environment to support outdoor activities during heat stress conditions. Outdoor activities and urban microclimate parameters were observed in selected public spaces of Sydney, Melbourne and Adelaide. Outdoor neutral and critical thermal thresholds are determined. An indexing system to indicate spatial heat resilience is presented. Correlations between spatial heat resilience and urban surface covers, and potential applications in low carbon cities are discussed. Results indicate that outdoor activities decrease after the neutral thermal threshold of 28-32°C. Critical zero-activity situations can occur in the range of 30-48°C. Particularly public spaces with more tree canopy and natural landscapes have more resilience to heat stress. Heat mitigation during summer results in increased outdoor living. Heat resilient public spaces can provide high-performance outdoor environments in the context of climate change.

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Keywords: Heat resilience; low carbon cities; public space vitality; urban microclimates

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1. Introduction

Australia will face at least 0.6 °C (best scenario: B1) and at most 3.8 °C (worst scenario: A1F1) increase in its surface temperature by 2090 [1]. However, warmer urban scenarios can significantly affect the liveability of cities [2, 3]. Cities have an essential public health agenda to adapt their built environment to the coming warmer climates [3, 4]. Increased indoor air-conditioned in hotter microclimates cause higher demand for energy consumption and greater waste production in cities [5, 6]. Increased demand for energy consumption for air-conditioning, lighting, and transportation is frequently accompanied by exhausted waste heat production. This anthropogenic heat in urban settings creates a feedback loop with heat stress in the built environment. The feedback loop between heat stress in public space, outdoor space denial, and heat-generating indoor behaviours in the urban environment exacerbates the damaging capacity of heat stress in cities.

In the context of increasing urban heat stress, this paper presents the concept of spatial heat resilience as the capability of the built environment to support outdoor activities during heat stress conditions. Methods to measure spatial heat resilience, correlations to urban surface cover materials and application in reducing the demand for energy consumption in Australian cities are under particular focus.

2. Heat stress in the built environment

Unusually high heat arising from a high daily temperature insufficiently discharged overnight is denoted as heat stress in heat-health scholarship [7]. Hard-landscaped urban areas tend to get hotter during the day and may stay warmer during the night compared with their rural vicinities. Such urban-rural temperature difference frequently reaches 2°C and can peak at more than 12°C (Gartland 2008; Oke 2006; Wong & Yu 2008). The intensity of the UHI effect tends to be maximised when nocturnal surface temperature is reported in winter under clear sky.

Oke [8] highlights the urban structure, cover, fabric and metabolism as the major contributing factors to the UHI effect. Meanwhile, external factors including regional climate, seasonal factor and reference sites affect the magnitude of the UHI effect [9-11]. The magnitude of the UHI effect is usually reported to be higher at night time [12]. As such the UHI effect is frequently known as a night time phenomenon in urban climatology [9, 13, 14]. The urban-rural temperature difference begins to develop in the afternoon and peaks during the night, concentrated in highly developed urban areas (see Fig. 2.11). Due to heat storage in urban surface covers and heat-trapping urban structure, the latent heat remains in the built environment during early night time [9, 15, 16] and causes the urban areas to have extended UHI effect during the night. Yet, the heat stress tends to be higher in the afternoon in the built environment.

While a comfortable thermal environment can enhance people's choices to spend more time outdoors, excess heat load can cause significant discomfort, altering the frequency and patterns of outdoor activities. Spatial configurations – contributing to urban microclimates – have the ability to alter the vitality of public space by providing thermal comfort and consequently facilitating outdoor activities.

Extensive thermal comfort research indicates that there are temperature ranges, in which the need for thermal adjustment is perceived to be neutral by most of the space participants (more than 80%) in the thermal sensation voting system [17]. In such thermal environments, occupants feel neither warm nor cold, and therefore, the ambient thermal conditions are perceived as 'neutral' [18]. The high threshold for thermal neutrality, measured via standard effective temperature (SET), is suggested to be 24.1°C for indoor steady state conditions [19]. Research in European context reveals up to 10°C variation in outdoors thermal neutrality in different cities [20]. A thermal comfort investigation in Sydney suggests that neutral temperature threshold in semi-outdoor environments (naturally ventilated buildings) is OUT_SET = 26.2°C [21]. Another Australian outdoor thermal comfort research reports comfortable outdoor temperature in summer varies between the minimum of 19.9°C (in Melbourne) and the maximum of 30.6°C (Adelaide in) [22].

Neutral thermal threshold (NTT) – in this study – refers to the upper limit of outdoor thermal neutrality. Indoor NTT is determined by the comparison between thermal sensation votes and indoor microclimate parameters (via SET indicator). Outdoor thermal environments change more rapidly compared with indoors. There is also limited chance to control the participants in outdoor environments. Heat sensitivity of outdoor activities may include changes in outdoor activity patterns, activity locations and in extreme conditions activity elimination.

2.1. Outdoor neutral thermal threshold (NTT_{out})

Heat sensitivity of outdoor activities starts after a determinable neutral thermal threshold is reached and is referred to as the outdoor neutral thermal threshold (NTT_{out}) in this paper. The NTT_{out} can be effectively determined based on the observation of outdoor activities. Outdoor activity-comfort research suggests that thermal adaptation is stronger and more frequent outdoors [23-25] due to alternative choices, climate expectations and individual differences compared with indoor steady state conditions [26, 27].

Heat-activity observation data could indicate a good approximations for the calculation of NTT_{out}. The NTT_{out} is identified as the heat-activity model breakpoint in segmented regression analysis (also known as piecewise regression). The breakpoint of the best-fit model in this study indicates the NTT_{out}.

2.2. Outdoor critical thermal threshold (CTT_{out})

Public spaces may experience zero-activity condition after a critical thermal threshold. This critical condition may be determined by experimented or projected data. The possible zero-activity condition is expected to occur after a certain equivalent temperature outdoors. Nevertheless, such critical zero-activity situations have uncertainty, due to the unpredictability of human behaviours. If the NTT_{out} is assumed as the first thermal environment index, the outdoor critical thermal threshold (CTT_{out}) is its complementary measure. The CTT_{out} explains the limits of outdoor thermal adaptation, where the NTT_{out} indicates the breakpoint of change in heat-activity model.

3. Materials and methods

The current case study focuses on general trends of heat sensitivity of outdoor activities. Therefore, physiological and psychological factors of participants were not taken into consideration. It was assumed that the randomly observed participants represent a sample of the general public in Sydney, Melbourne and Adelaide (who use the public spaces). Case study public spaces were observed for more than 200 times during a year starting in February 2013 to ensure the validity of data. During each round of observation, which lasts for five minutes, citizens' outdoor activity patterns were printed on prepared field study maps. Microclimate data including temperature, humidity and wind speed is collected before and after each activity observation via three fixed weather data loggers (EXTECH RHT20 with temperature-humidity sensors) installed exposed to wind flow and 1.5m above the ground surface (mimicing the conditions that is experienced by random human participants). A portable weather station was used to ensure the calibration of data loggers (Kestrel 4000). Hygrometer data loggers were installed at the observation point before observations started.

The observation points were Darling Harbour in Sydney (including Friendship Plaza, Darling Quarter and Darling Harbourside), Federation Square in Melbourne (including St. Paul's Court, Central Plaza and Federation Wharf) and Festival Centre in Adelaide (including Hajek Plaza, Torrens Riverbank, Art Centre Plaza and Blue Hive Plaza). These public spaces present three contemporary multi-functional public spaces with microclimates and activity diversity (see Fig. 1).

3.1. The universal thermal comfort index (UTCI)

The universal thermal comfort index (UTCI) is selected as the most advanced outdoor thermal discomfort indicator [28]. The universal thermal comfort index (UTCI) is an equivalent temperature which indicates the multi-node effect of the thermal environment on the human body. The UTCI is the air temperature of the reference environment that provides a similar physiological response to the complex outdoor thermal environment. Effective parameters are air temperature, humidity, wind speed, radiant temperature, and adaptive clothing [29]. A complete adaptive UTCI model considers details such as individual's weight, body surface area, and exposure time that are not focused in this paper. Therefore, a simplified calculator of UTCI is used in this paper that is accessible at http://www.utci.org/.

Fig. 1. Darling Harbour (Sydney), Federation Square (Melbourne) and Festival Centre (Adelaide) are three multi-functional public spaces with diverse space configurations, and supportive land uses (Photos: Author, November 2014).

3.2. Statistical analysis

Correlation and regression analysis are the main data analysis methods in this paper. In correlation analysis, the correlation coefficient (r) value indicates the relationship between variables. The r-values closer to +1 indicate stronger positive relationship, and an r-value closer to -1 indicates a strong negative dependency (zero r-value indicates that the two variables are not related). Detailed dependency between two variables may be analysed via regression analysis. The coefficient of determination (R-squared) indicates how well data fits a statistical model. The R-squared ($R^2 = r^2$ in linear regression model) may vary between 0 and +1. Closer R-squared values to +1 indicate higher goodness-to-fit of a model. The significance level of the model is determined via the p-value. The p-value is being compared with a threshold valueof 0.05 in social sciences [30, 31]. The p-values smaller than 0.05 in regression analysis is considered as a reliable model to predict future scenarios with more than 95% confidance.

Segmented regression analysis is used when there are at least two different identifiable patterns in the bivariate data distribution. It is vital to identify probable breakpoints in the segmented regression model. One way to choose appropriate regression breakpoints is to conduct separate linear regressions on discrete samples of each data distribution (one at a time), and select the highest R^2 values and *p*-values (these two scores do not necessarily increase together). Distribution breakpoint(s) may be identified visually through the scatterplot diagram (via trial and error). The regression analysis is conducted for data between the identified segments. Goodness-of-fit is identified via the lowest *p*-value and highest R-squared value (R^2).

4. Thermal thresholds of outdoor activities

Outdoor activities' distribution (in UTCI scale) in Friendship Plaza, Darling Quarter and Harbourside (Sydney) is presented in Fig. 2 (similar analysis was done for other case study public spaces). The analysis of the heat-activity distribution reveals that outdoor activities decrease from their ideal quantities in UTCI < 20°C. Comparison of this observation with outdoor thermal discomfort literature indicates that the lower boundary of outdoor thermal discomfort zone may also have a different value than its indoor equivalent, which is commonly suggested to be 18°C. Results of heat-activity observations indicate that all outdoor activities are sensitive to outdoor heat stress. However, their neutral thermal zone, critical breakpoints, and degree of heat sensitivity vary for necessary, optional, and social activities. Spatial configurations and supportive land uses are other influential factors in heat sensitivity of outdoor activities. After the thermal environment surpasses the NTT_{out}, outdoor activities begin to decrease, and also become less diverse and more limited to necessary and planned activities.

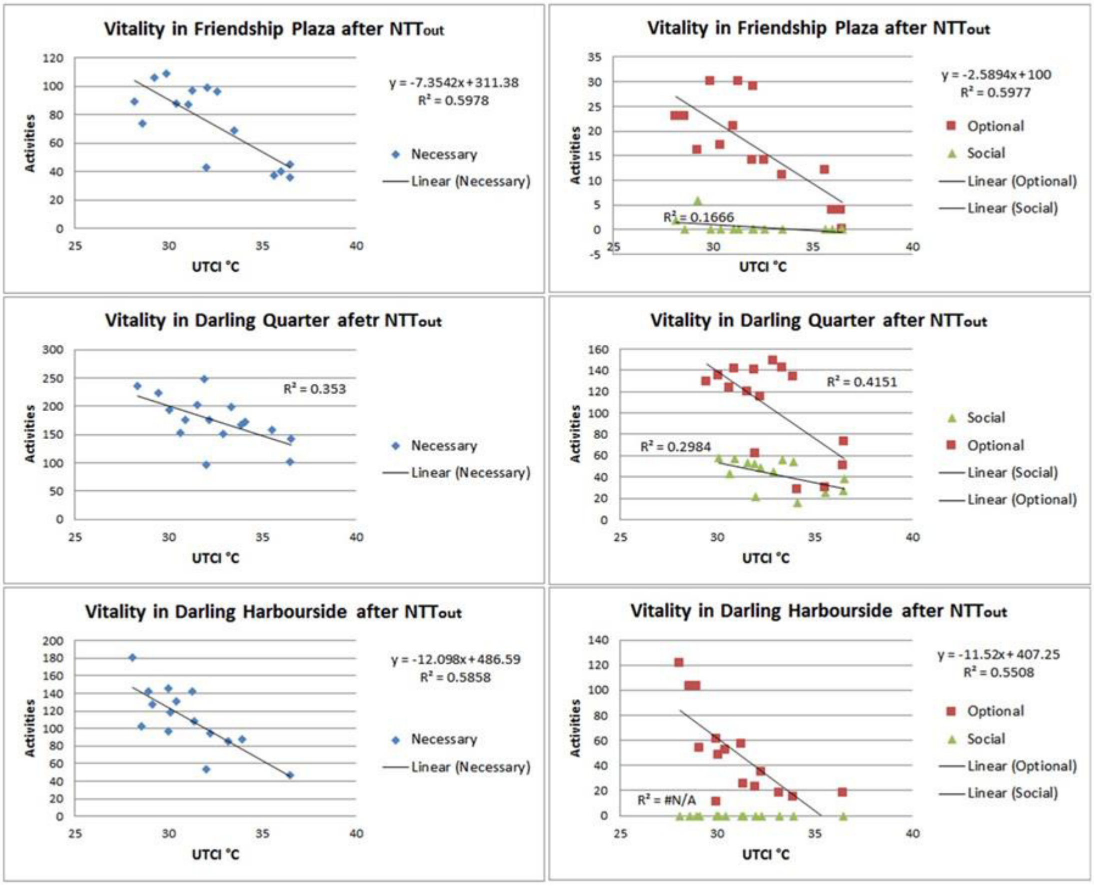

Fig. 2. Observed necessary, optional and social activities in Friendship Plaza, Darling Quarter and Harbourside (Sydney) between February 2013 and March 2014.

Necessary activities have a higher resilience to heat stress compared with optional and social activities in a majority of case study public spaces with higher NTT_{out} and CTT_{out} measures (see Table 1). Such heat resilience is higher in public spaces with strong surrounding land use support, such as Federation Central Square (Melbourne), and Darling Quarter (Sydney). Higher heat resilience in necessary activities occurs mainly due to the support of non-climate factors such as citizens' daily walking journeys from home to work, and their shopping habits.

Optional activities have lower heat resilience compared with necessary activities in a majority of case study public spaces (excluding Torrens Riverbank). Larger decreases in optional activities during heat-stress conditions are mainly due to the stronger contribution of the factor of choice. Well-supported public spaces (in terms of surrounding land use) have higher heat resilience and represent the lowest rate of optional activity decline. Space users who must persist with their necessary daily activities at higher temperatures, begin to refuse optional attendance in spaces with less supportive facilities.

Heat resilience of social activities varies significantly compared with necessary and optional activities. In public spaces with strong supportive land uses and planned events, social activities are as heat-resilient as necessary activities. Examples are Federation Central Plaza, and Darling Quarter. However, in the absence of supportive facilities and planned events, social activities are extremely heat-sensitive and begin to disappear immediately after NTT_{out}. Examples are Blue Hive Plaza, Hajek Plaza, and Darling Harbourside. Findings confirm the heat sensitivity of optional activities as claimed by Gehl [32, 33]. However, as discussed, necessary and social activities are also heat-sensitive and in some cases such as Torrens Riverbank (Adelaide) have lower heat resilience compared with optional activities.

Table 1. Neutral and critical thermal thresholds of necessary, optional and social activities in 10case study public spaces.

	Necessary		Optional		Social	
	NTT_{out} (°C)	CTT_{out} (°C)	NTT_{out} (°C)	CTT_{out} (°C)	NTT_{out} (°C)	CTT_{out} (°C)
Friendship Plaza	28	40	28	38	28	30
Harbourside	28	42	28	42	N/A	28
Darling Quarter	30	50	30	46	30	N/A
Central Plaza	48	48	48	48	N/A	N/A
Federation Wharf	31	48	29	48	29	46
St. Paul's Court	33	48	26	43	24	44
Art Centre Plaza	30	44	30	42	30	32
Blue Hive Plaza	27	45	22	42	34	40
Hajek Plaza	28	45	27	38	28	28
Torrens Riverbank	28	45	34	48	34	40

4.1. Limitations in the projection of NTT_{out} and CTT_{out}

Projected outdoor heat-activity critical limits and thermal thresholds (CTT_{out}) depend on the assumption that the form of relationship is maintained at higher temperatures than observed. The estimation of future heat-activity patterns may experience another step change. Since the thermal environment becomes extremely uncomfortable for humans in UTCI > 45°C, sudden step changes (new breakpoints) at higher temperatures are probable [34].

A possible step change in activities during extreme heat-stress conditions could make Festival Centre completely vacant, Rundle Mall a very costly space to operate and, Hindmarsh Square, Torrens Riverbank, Federation Square and Darling Harbour very hard to access. Such probable (and experienced) step change refers to the prominent avoidance of outdoor activities resulting from the extreme heat-stress in public space. In such circumstances, citizens may not participate outdoors at all; and to access entertainment, recreation or shopping attractions people are required to walk over extremely hot urban surfaces for a distance.

The question then arises of whether there is any correlation between an SHR index and surface cover materials in public spaces. Probable correlations can assist the design of heat-resilient public spaces in Australian cities.

There is no evidence indicating that the values of NTT_{out} and CTT_{out} are dependent. However, they may be influenced by similar factors such as spatial configurations, functions, and surface covers. The NTT_{out} reflects the starting point of heat sensitivity of outdoor activities and is significantly affected by spatial configurations and participants' adaptive reactions. Meanwhile, CTT_{out} reveals the maximum capability of outdoor activities to resist heat stress in public spaces. Thus, both values must be considered when assessing spatial heat resilience.

5. Spatial heat resilience index (SHR Index)

Having a single-value indexing system for spatial heat resilience (SHR Index) makes the comparison less complicated and more suitable for decision-makers, and urban designers. Therefore, SHR index can be calculated as follows:

$$SHR\ Index\ (°C) = mean\ (\frac{\sum_1^i NTT_{out}}{i} + \frac{\sum_1^j CTT_{out}}{j})$$

Table 2 shows the SHR Index Thus, Federation Central Plaza has the highest resilience to heat stress with an SHR index = 48 °C (the high SHR index in Federation Central Square is significantly affected by supportive land uses and event management). Federation Wharf, Darling Quarter, and Torrens Riverbank have high heat resilience in the range of SHR index = 39 °C. In the SHR index range of 35 °C to 38.75 °C, St. Paul's Court, Art Centre Plaza and Darling Harbourside have medium (acceptable) SHR index. These public spaces maintain their vitality during heat stress conditions at an acceptable rate.

Table 2. The SHR index and SHR-ID for case study public spaces in Sydney, Melbourne, and Adelaide.

	SHR index	SHR-ID
Federation Central Plaza	48	High
Federation Wharf	39	
Darling Quarter	39	
Torrens Riverbank	38.75	
St. Paul's Court	37.5	Medium
Art Centre Plaza	36.5	
Darling Harbourside	35	
Hajek Plaza	34.5	Low
Blue Hive Plaza	34	
Friendship Plaza	33.5	

Hajek Plaza, Blue Hive Plaza, and Friendship Plaza, however, have an SHR index lower than 35 °C. This means that these public spaces are not supporting outdoor activities during heat-stress conditions. Such low SHR indexes indicate unwillingness of people to attend outdoor activities due to the high risks of heat-stress conditions and inability of these public spaces to mitigate such risks. Based on heat-activity observations in Sydney, Melbourne, and Adelaide, SHR index thresholds of 35 °C and 39 °C are suggested to identify the relative thermal performance of other public space compared to the studied cases.

For example, Torrens Riverbank have high SHR indexes of around 39 °C, which is sufficient to support a reasonable amount of activities on more than 89% of Adelaide's summer days (based on a daily maximum temperature frequency of $T < 39°$ in summer days of 2012–2015 between December and February). Space users who must persist with their necessary daily activities during heat stress conditions begin to refuse optional attendance in public spaces with less greenery. Optional activities in hard-landscaped public spaces such as Hajek Plaza and Blue Hive Plaza have the lowest resilience to heat. Outdoor activities begin to disappear (with zero values) from public spaces immediately after NTT_{out} is reached in artificial-hard landscaped public spaces (with low shadow coverage).

5.1. Correlations between SHR index and urban surface covers

Urban surface coverage of Festival Centre (Adelaide), Federation Square (Melbourne), and Darling Harbour (Sydney) was reconstructed via desktop extraction of visible urban surface cover from Google Earth images in i-Tree Canopy. The proportional coverage of tree canopies, grass cover, paving, asphalt, and natural-hard landscapes in each public space was calculated. Table 3 shows the ratio of surface cover classes and shading in analysed images. Hard-landscape covers including paving, asphalt, and natural-hard landscape materials such as wood chips and bare land are dominant in a majority of case study public spaces. The only public spaces with more than 50% soft-landscaped area (tree canopy and grass cover combined) were Torrens Riverbank.

Table 2 shows that Federation Wharf, Darling Quarter, and Torrens Riverbank have the highest SHR indexes among case study public spaces (excluding Federation Central Plaza). Thus, there is a correlation between the high ratio of tree canopy and high SHR index in case study public spaces. Although this primary result does not have statistical support, it indicates a potential positive correlation between urban green cover and heat resilience in public spaces.

Table 3. Ratio of surface cover classes in case study public spaces (estimated via i-Tree Canopy).

	Tree canopy	Grass cover	Paving	Asphalt	Natural-hard landscape	Shade
Friendship Plaza	18%	1%	66%	0%	7%	8%
Darling Harbourside	0%	0%	51%	0%	41%	8%
Darling Quarter	20%	7%	48%	0%	15%	10%
Federation Central Plaza	4%	4%	74%	0%	0%	18%
Federation Wharf	32%	5%	9%	41%	9%	4%
St. Paul’s Court	5%	0%	77%	0%	2%	16%
Art Centre Plaza	0%	0%	48%	0%	41%	11%
Blue Hive Plaza	2%	0%	86%	0%	0%	12%
Hajek Plaza	0%	2%	65%	14%	18%	1%
Torrens Riverbank	12%	53%	19%	10%	5%	1%

Correlation coefficient (*r*) values of SHR index and the ratio of different surface cover classes in public space are shown in Table 4 (Federation Central Plaza data is excluded in this section due to its uncertain SHR index). The SHR index has a strong negative (downhill) correlation to artificial-hard landscape (*r*-value = -0.70), weak negative correlation to natural-hard landscape (*r*-value = -0.16), and medium positive correlation to tree canopy (*r*-value = 0.61) and grass cover (*r*-value = 0.51). Thus, in a prototype public space, the high ratio of artificial-hard landscaping correlated with low heat resilience (represented by SHR index), whereas the high ratio of urban greenery (including tree canopy and grass cover) indicates high resilience to heat stress.

Table 4. Correlation coefficient (*r*) values between the ratio of surface cover classes and SHR index.

Surface cover class	r-value	Correlation
Artificial-hard landscape	-0.70	Strong negative
Natural-hard landscape	-0.16	Weak negative
Tree canopy	0.61	Medium positive
Grass cover	0.51	Medium positive

A comparison between Tables 2 and 3 shows that when the ratio of tree canopy varies between zero and 20% the highest variation in SHR index is visible. In the lower range (TC < 20%), every 5% increase in urban tree canopy increases the SHR index by 1.5 °C. The SHR index increases only 0.5 °C between tree canopy ratios of 20% and 30%, and stays almost constant thereafter. As such, where necessary activities are not dominant and tree canopy ratio is lower than 30%, a high tree canopy ratio indicates a high SHR index – meaning that increased tree canopy results in increased resilience to heat stress in urban settings.

5.2. Low carbon living in heat resilient urban settings

The primary assumption in this paper is that outdoor space participants can be excluded from indoor attendants – who use air-conditioning during heat stress conditions. After neutral thermal thresholds, each 1.0 °C increase in outdoor temperature causes an outdoor activity decrease rate of between 1.9% and 2.5% (excluding public spaces with very strong land use support and high rate of necessary activities such as Rundle Mall and Federation Square). Thus, for each 1.0 °C increase in outdoor heat stress, roughly a 2.2% decrease in outdoor activities is expected.

A complementary heat-activity choice survey in Adelaide (N=267) revealed that more than 34% of citizens had daily outdoor activities, and nearly 15% of the surveyed population expressed no willingness to attend outdoors during heat stress conditions (such unwillingness rate is only 2% in warm thermal conditions). Thus, the difference between no outdoor activity in hot and warm thermal conditions is 13%. Thus 13% of the 34% of total urban population - who had daily outdoor activities - preferred not to attend outdoors during heat stress conditions, whereas they attend outdoors in warm thermal environments (34% x 13% = 4.42%).

Resulted 4.42% variation in outdoor activities during heat stress conditions can be used as a multiplier in the cooling energy demand projections in further studies. This survey was related to Adelaide; Therefore, projections for Melbourne and Sydney requires similar research.

6. Conclusions

Heat resilient built environment supports vitality and usability of public spaces, especially during the stressed microclimates of summer heatwaves. Necessary, optional and social activities start to decrease after the NTT_{out} of 28-32°C. Critical zero-activity situations can occur between the CTT_{out} of 30-48°C. Spatial heat resilience (SHR) is presented to indicate the capability of the built environment to support outdoor activities during heat stress conditions. Public spaces with high heat resilience have SHR indexes in the range of 39°C (in UTCI scale). SHR < 35°C indicates high heat sensitivity in a city with a temperate climate. The SHR index of a public space can be identified via observation or simulation.

Urban greenery has positive influence on outdoor activities and public health [35-37]. Urban greenery is argued to promote health, well-being, and social safety in the living environment [38, 39]. This case study indicates that – where necessary activities are not dominant and tree canopy ratio is lower than 30% (i.e. a majority of Australian urban settings) – increased tree canopy results in increased heat stress resilience. Necessarily, optional and social activities in greener spaces have a higher resilience to heat stress. Hear resilient public spaces contribute to 4.42% decrease in cooling energy demand during summer in Australian cities. In the context of climate change, spatial heat resilience can support more vibrant, healthy and safer urban environments in low carbon cities.

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