# Socio-environmental impacts of heat stress in public spaces of Australian cities: spatial heat resilience and its application in low carbon cities

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## Abstract

Urban spaces are experiencing warmer microclimates as the combined result of climate change and the Urban Heat Island (UHI) effect. While climate change projections indicate a likely increase of 2°C in Australia by 2070, an additional heat load of 10°C exists in the built environment. The question is how and to what extent contemporary public spaces can become more resilient to such high temperatures?

This PhD research investigates the social impacts of heat stress in Australian cities. Two intertwined concepts of Spatial Thermal Resilience (indicating physical ability to maintain thermal environment close to humans' thermal comfort) and Activity Thermal Resilience (indicating ability to maintain normal activities in the thermal discomfort conditions) are proposed and tested in three case studies in Darling Quarter (Sydney), Federation Square (Melbourne) and Hajek Plaza (Adelaide). Data collection includes thermal photography, climate measurement and direct observation (air temperatures range: 16-42°C; surface temperatures range: 10°C- 65°C). The data is analysed via correlational and regression analysis and findings are triangulated via a closed questionnaire survey.

Results indicate that necessary, optional and social activities in public spaces with soft landscapes (facilitated by urban greenery and controllable surface water) and smart shadow coverage have higher STR values. Optional activities (including preferred and adjustable activities) start to decline after the apparent temperature reaches the threshold of 28-32°C. However, necessary activities (including vital and habitual) and social activities (including simultaneous, managed and cultural) have a higher neutral thermal threshold of 36°C. Research findings contribute to urban design knowledge by providing STR and ATR as quality indicators for public space and a set of guidelines to facilitate more heat-resilient urban spaces.

## Keywords

Urban Heath Island effect, Australian cities, public space qualities, outdoor activity patterns, urban microclimates, urban landscape, surface materials, urban structure.

## Research collaborations

The proposed research is linked to the new Cooperative Research Centre for Low Carbon Living (CRC-LCL) project on Urban Microclimates (program 2, project 9). The Urban Microclimates project will develop a cross-disciplinary, multi-scale understanding of Australian cities’ microclimates, by focusing on the Urban Heat Island (UHI) effect and the interplay between urban form, density, surfaces and ambient temperature. It will be undertaken collaboratively by researchers from UniSA, UNSW, UniMelb, the CSIRO, the CRC for Water Sensitive Cities, the City of Sydney, the City of Melbourne, the City of Adelaide, government bodies and industry partners.

# Introduction

Australia is expecting a likely increase of 2-5°C in its surface temperature by 2070 ([OECD, 2010](#_ENREF_49); [Ricketts & Hennessy, 2009](#_ENREF_53)). Summer heatwaves are now more frequent and extended in Australian cities. Australia experienced seven extreme heatwaves in 1908, 1939, 1960, 1973, 2004, 2009 and 2013 ([BoM, 2008](#_ENREF_4); [Nairn & Fawcett, 2013](#_ENREF_37)). During summer heatwaves, public spaces are frequently warmer than human’s thermal comfort level in a majority of Australian Cities ([BoM, 2008](#_ENREF_4); [Ricketts & Hennessy, 2009](#_ENREF_53); [Williams, Nitschke, Weinstein, et al., 2012](#_ENREF_68)).

The excess heat load in urban settings can reach up to 10°C compared to their peri-urban surroundings. In response to such substantial extra heat load in cities, citizens increasingly move into air-conditioned buildings during hot summer days to benefit from the indoor thermal comfort. However, exhausted heat generated from indoor air-conditioning causes an ever-increasing outdoor temperature ([Ichinose, Matsumoto, & Kataoka, 2008](#_ENREF_25)). Such anthropogenic (human-made) heat is cited as a key contributor to the artificial heat load in cities, which is well known as the urban heat island effect ([Erell, Pearlmutter, & Williamson, 2011](#_ENREF_15); [Gartland, 2008](#_ENREF_17); [Oke, 2006](#_ENREF_51)).

The excess urban heat stress affects citizens’ health, especially in regards to more vulnerable groups such as the elderly and children during summer heatwaves ([Hu, Becker, McMichael, & Tong, 2007](#_ENREF_24)). Amplified heat stress during summer heatwaves causes more than 1000 extra annual deaths and contributes significantly to heat related morbidity in Australia ([Kirch, Menne, & Bertollini, 2006](#_ENREF_27); [Major Cities Unit, 2013](#_ENREF_34); [McMichael et al., 2003](#_ENREF_35); [Nitschke, Tucker, & Bi, 2007](#_ENREF_48); [Steffen, Hughes, & Perkins, 2014](#_ENREF_60); [Wendt, Van Loon, & Lichtenbelt, 2007](#_ENREF_65); [Williams, Nitschke, Sullivan, et al., 2012](#_ENREF_67); [Williams, Nitschke, Weinstein, et al., 2012](#_ENREF_68)). The combination of summer heatwaves and the urban heat island effect has increased the risk for outdoor public life.

# Literature review

The vitality of human activities in public space is the core concept of significant and contemporary public life studies ([Burton & Lynne, 2006](#_ENREF_8); [Dobbins, 2009](#_ENREF_13); [Jan Gehl, 1987](#_ENREF_18); [Lang, 1987](#_ENREF_28); [Moughtin, 2003](#_ENREF_36); [Whyte, 1980](#_ENREF_66)). The underlying argument is that the built environment can significantly affect outdoor activities and simultaneously, it is impacted by people’s social and behavioural norms and actions ([Jan Gehl, 2010](#_ENREF_20); [Lang, 2005](#_ENREF_29)). Therefore, the concept of ‘public space and public life’ argues that vibrant public life is the result of quality public spaces and is also a significant contributor in shaping such quality ([Bosselmann, 2008](#_ENREF_5); [Jan Gehl, 1987](#_ENREF_18), [2010](#_ENREF_20); [Lillebye, 2001](#_ENREF_31)).

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. Thus, the spatial configurations, contributing to urban microclimates have the ability to alter the vitality and utilisation of public space by providing thermal comfort and consequently facilitating optional outdoor activities. Urban structure, surface materials and landscape are examples of such urban microclimate contributing factors.

Urban microclimates are the complex outcome of spatial and climatic variables and can affect outdoor activity patterns, especially when there is a factor of choice ([Bosselmann, Arens, Dunker, & Wright, 1995](#_ENREF_6); [Jan Gehl, 1987](#_ENREF_18), [2010](#_ENREF_20); [Marialena Nikolopoulou, 2011](#_ENREF_42)). However, recent studies on urban microclimates focus more on the physicality of the space ([Correa, Ruiz, Canton, & Lesino, 2012](#_ENREF_11); [Johansson, 2006](#_ENREF_26); [Lin, Matzarakis, & Hwang, 2010](#_ENREF_33); [Shashua-Bar, Tzamir, & Hoffman, 2004](#_ENREF_54)), rather than discussing how physical attributes of spaces can alter outdoor activities.

Outdoor thermal comfort is a factor which affects outdoor activities in public space ([Bosselmann et al., 1995](#_ENREF_6); [Eliasson, Knez, Westerberg, Thorsson, & Lindberg, 2007](#_ENREF_14); [Jan Gehl, 1987](#_ENREF_18); [Marialena Nikolopoulou, Baker, & Steemers, 2001](#_ENREF_44)). In general, thermal comfort is defined as the state of mind that expresses satisfaction with the thermal environment ([ASHRAE, 2013](#_ENREF_2)). While the surrounding built environment can justify the primary microclimate conditions for thermal comfort, it is the human’s brain that identifies if the body is thermally comfortable or it is under heat stress. Focusing on the effect of microclimates on humans, a number of indoor thermal comfort investigations have been undertaken since the 1960s ([Auliciems, 1969](#_ENREF_3); [Fanger, 1982](#_ENREF_16); [Givoni, 1998](#_ENREF_23); [Oke, 1988](#_ENREF_50); [Olgyay & Olgyay, 1963](#_ENREF_52)). Indoor thermal comfort studies result in the development of a number of steady state thermal comfort (SSTC) models, in which thermal comfort preferences are defined based on microclimate factors of air temperature, humidity, airflow and radiation in addition to human’s metabolic rate and clothing isolation ([Stathopoulos, Wu, & Zacharias, 2004](#_ENREF_56); [Walton, Dravitzki, & Donn, 2007](#_ENREF_63)).

While many studies of outdoor thermal comfort concentrate on physical factors of microclimate ([Walton et al., 2007](#_ENREF_63)), more advanced investigations indicate that the state of adaptation to outdoor microclimates is an influential factor in comfort sensations ([Lin, 2009](#_ENREF_32); [Marialena Nikolopoulou & Steemers, 2003](#_ENREF_47)). Despite the SSTC models, which considers people as passive occupants of the space exposed to external microclimates, the adaptive thermal comfort argues that thermal comfort contributing factors are beyond the physical environment. The extent of feeling of comfort is a dependent variable of physical, psychological and psychological factors of the human-climate systems. Accordingly, thermal comfort is perceptual and varies depending on the psychological condition of participants, their expectations and adaptation level, their physiological conditions and the microclimate of the space in which they are placed ([Nicol, 1993](#_ENREF_39); [Marialena Nikolopoulou, 2004b](#_ENREF_41); [Szokolay, 2008](#_ENREF_61)).

People adapt themselves to microclimate conditions by selective activities such as clothing and sunlight exposure-prevention ([Marialena Nikolopoulou & Lykoudis, 2007](#_ENREF_46); [Spagnolo & de Dear, 2003](#_ENREF_55)), while the level of social activities can also influence the outdoor thermal comfort sensation ([Aljawabra & Nikolopoulou, 2010](#_ENREF_1)). The adaptive thermal comfort (ATC) concept is multi-variable and complex and discuss thermal comfort not only dependent on microclimate physical factors, but also dependent on demographic characteristics such as gender and age, health, psychological states such as happiness and stress ([Cooper, 1982](#_ENREF_10); [Szokolay, 2008](#_ENREF_61)), adaptive actions (e.g. clothing), and general expectations of the climate ([Candido, 2011](#_ENREF_9); [de Dear, Leow, & Foo, 1991](#_ENREF_12); [Marialena Nikolopoulou & Lykoudis, 2007](#_ENREF_46); [Wang, Zhang, Zhao, & He, 2010](#_ENREF_64)).

Gehl ([1987, p. 11](#_ENREF_18)) argues that optional activities are the only ones that are influenced (notably) by urban microclimates. As such, Gehl suggests that to make vibrant public spaces, particular focus is needed on supporting optional activities. However, Gehl’s studies on quality of public space and public life considered climate (long-term) and weather (short-term) as controlled variables to investigate public life in ideal weather conditions (respective case studies are done on sunny days in spring and autumn).

# The gap in the literature

Existing studies on the effect of public space structure and elements on urban microclimates are likely to focus more on physical factors (e.g. urban vegetation and spatial ratio) ([Correa et al., 2012](#_ENREF_11); [Johansson, 2006](#_ENREF_26); [Lin et al., 2010](#_ENREF_33); [Shashua-Bar et al., 2004](#_ENREF_54)) rather than on discussing how these physical attributes can alter activities in outdoor space.

The links of public space quantities and quality with the UHI effect are still not clear. The effect of sun, wind, trees and water on people’s attendance in public space has been under research since the 1980s ([Givoni, 1998](#_ENREF_23); [Whyte, 1980](#_ENREF_66)). Whyte’s study on public life in small urban spaces in New York City was a good start, which has not been pursued thoroughly in further research. Majority of studies have looked at public space microclimates through absolute physical and quantitative lenses ([Erell et al., 2011](#_ENREF_15); [Gartland, 2008](#_ENREF_17); [Givoni, 1998](#_ENREF_23); [Ichinose et al., 2008](#_ENREF_25); [Oke, 2006](#_ENREF_51); [Wong & Yu, 2008](#_ENREF_69)), whilst a few public life monitoring studies focus on pedestrian flow in ideal climate situations ([Jan Gehl, 1987](#_ENREF_18), [2010](#_ENREF_20)).

# Aims and Objectives of the Study

This research aims to explore the potential links between public space physical dimensions (and elements), and embodied activity patterns during heat stress conditions. In particular, it studies the effects of physical attributes of public space and artificial heat stress (the UHI effect) on citizens’ behavioural patterns, the effect of these behavioural patterns on quality of public space and the role of heat resilience in low carbon cities. The study also aims to explore opportunities to transform existing public spaces to more heat resilient and support low carbon living principles in Australian cities. Accordingly, the objectives of current research are to:

1. Facilitate research on social impacts of urban microclimates and their essential characteristics in Australian context
2. Explore the links between public space quality and quantities, during heat stress conditions
3. Defining heat resilience in public space and its application in liveability assessment of existing and future cities
4. Explore opportunities to facilitate Low Carbon Living principles in heat resilient cities

# Research Key Questions

The current research will explore how the outdoor thermal environment variables can alter activity patterns in public space, and how heat resilient public spaces can support low carbon living principles. In order to investigate the research criteria and provide a more explicit understanding of probable correlations, the following three key research questions are proposed to be explored:

1. What outdoor activity patterns are sensitive to heat stress in public space and to what extent do they correlate with the urban microclimate key contributors? When do changes start and how do changes fluctuate?
2. What attributes of public space can facilitate resilience to heat stress?
3. To what extent can heat resilient public spaces reduce anthropogenic waste heat and facilitate low carbon living in Australian cities?

# Methodology

Public life in contemporary cities involves a variety of users with diverse expectations of climate and cultural responses to combat heat stress in public space. Citizens perform a diverse range of choices during heat stress conditions, ranging from preventing outdoor attendance to wet sports and indoor shopping.

Major investigations of public space and public life in Australian cities have been conducted based on pedestrian flow and stationary outdoor activities in ideal climate conditions ([Jan Gehl, 2002](#_ENREF_19), [2011](#_ENREF_21)). The climate and weather conditions are considered as controlled variables, and data was collected during sunny spring or autumn days when the temperature varied between 18°C and 28°C. Building upon the existing public life studies in Australian cities, I investigated outdoor neutral temperature thresholds for three public spaces in Adelaide, Melbourne and Sydney with the aid of direct observations and microclimate measurements. The selected case studies represent three typical public spaces in regards to their microclimates and embodied activity patterns. The selected public spaces for this study are Darling Quarter (Sydney), Federation Square (Melbourne) and Hajek Plaza (Adelaide).

## Thermal-load measurement

The SSTC standards predict the mean thermal sensation of large populations, based on thermal comfort indices such as predicted mean vote (PMV) and standard effective temperature (SET). Considering the physiological and psychological variables of outdoor thermal comfort, outdoor thermal comfort is commonly predicted based on dry-bulb temperature, vapour pressure (or relative humidity), air velocity, and net radiation absorption in SSTC models.

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 Adelaide, Melbourne and Sydney (who use the public spaces). Each space was observed for more than 80 times during a year starting in February 2013 to ensure the validity of data. During each round of observation, which lasts for ten minutes, citizens’ outdoor activity patterns were coded into necessary, optional and social activities and 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, installed in permanently shadowed areas, exposed to wind flow and 1.5m above the ground surface. A portable weather station was used to ensure the calibration of data loggers. Hygrometer data loggers had been installed at the observation point before our observations started (they had been calibrated with the portable weather station unit).

It is widely argued that the outdoor thermal environment cannot be explained only by dry-bulb temperature ([Erell et al., 2011](#_ENREF_15); [Marialena Nikolopoulou, 2004a](#_ENREF_40); [M Nikolopoulou, Baker, & Steemers, 1999](#_ENREF_43); [Spagnolo & de Dear, 2003](#_ENREF_55)). A primary temperature-humidity index (THI) has been introduced by Thom ([1959](#_ENREF_62)). The THI gives an equivalent temperature in degree centigrades based on dry-bulb temperature and relative humidity. The THI is claimed to be a suitable measure for humans’ thermal-load (or discomfort) in public space ([Thom, 1959](#_ENREF_62)) and can be calculated as:

THI = T – (0.55 - 0.0055 RH) × (T-14.5)

The effect of wind flow is neglected in the THI. However, wind flow is a prominent factor in people outdoor living in the case of Adelaide especially during summer ([BoM, 2008](#_ENREF_4); [Nairn & Fawcett, 2013](#_ENREF_37)). Apparent Temperature (AT) is also used as an indicator of the perceived equivalent temperature by humans. The benefit of AT to THI is the consideration of human biology (by using skin vapour pressure instead of relative humidity) and wind flow in thermal comfort calculation. Steadman defines AT based on dry-bulb temperature, vapour pressure and wind speed ([Steadman, 1979](#_ENREF_57), [1984](#_ENREF_58)), and applies the AT in the study of semi-outdoor thermal comfort in Sydney, Australia ([Steadman, 1994](#_ENREF_59)):

AT = T + 0.33 × VP − 0.70×WS − 4.00

where T = dry bulb temperature (°C)

VP = water vapor pressure (hPa) [representing humidity]

WS = wind speed (m/s) at an elevation of 10 meters

The vapor pressure can be calculated from the temperature and relative humidity using the equation:

VP = RH / 100 × 6.105 × exp ( 17.27 × T / ( 237.7 + T ) )

where RH = Relative Humidity (%)

exp (x) = exponential function = ex

e (Euler number) =  2.718281828

The AT is also known as heat index and humidex. Outdoor thermal discomfort also depends on activity rate and clothing insulation of space participants ([Marialena Nikolopoulou, 2004b](#_ENREF_41); [Marialena Nikolopoulou & Lykoudis, 2006](#_ENREF_45)). However, clothing and activity factors may vary significantly based on the level of individual thermal adaptation. Since the focus of the current case study is on a large number of public space participants, activity and clothing factors are not taken into consideration. AT is used as the official thermal comfort indicator by the Australian Bureau of Meteorology and, therefore, is taken in this research as the closest indicator of outdoor thermal comfort in Australian cities

## Data collection framework

Microclimate indicators and activity patterns in each public space were observed and mapped in 10-minute intervals during hourly periods. Observations were limited to working hours between 10 am to 5 pm during weekdays to ensure the consistency of the collected data. Activity patterns and users of the public spaces change significantly during weekends, and this weekly change represents different characteristics for the selected public spaces (weekend activities can still inform some aspects of the public life but are out of the scope of this study). Therefore, weekends and public holidays are not included in the final data. Rainy and stormy days were also excluded.

Frequency and location of walking, working, sitting, standing, lying down, meeting, eating, children playing, sport, music playing and socio-cultural activities were recorded on observation sheets, and then transferred to data sheets. Based on the adopted theory of public space and public life ([J. Gehl & Svarre, 2013](#_ENREF_22)), activity patterns were categorised into necessary (including walking and working), optional (including standing, sitting, lying down, and individual eating and sport) and social activities (including group playing, eating and cultural activities) for data analysis. Activity patterns in Hindmarsh Square, Rundle Mall and Hajek Plaza were monitored, coded and mapped in different seasons to ensure that seasonal changes in activity patterns do not significantly affect the results.

Because of the differences in the function of selected public spaces, it is not accurate to compare the number of users and their activity patterns across the cases. The focus is on the comparison between activity patterns during heat stress and average thermal conditions in each case study. Therefore, the proposed spatial heat resilience of each space is based on a comparison between its normal and heat stress conditions and the normalised results are being compared to investigate which space has the higher heat resilience.

## Correlation, and linear regression analysis

Data was analysed via scattergrams, correlational and linear regression analysis to investigate the effect of AT on outdoor activity patterns. Correlation analysis (also known as contingency test) is one of the most common statistical tests to identify connections in quantitative research. Correlation coefficient value (varies between 0 and ±1) shows the strength and direction of the relationship between variables ([Bryman, 2008](#_ENREF_7); [Neuman, 2011](#_ENREF_38)). Correlation coefficient (*r*) values closer to +1 represent stronger positive relationships between the two variables, while closer *r*-values to -1 indicate strong negative dependency (i.e. variable A decreases with increase in variable B) and *r*-value = 0 indicate no connection.

Linear regression is used to explore probability and in-detail dependency among two observed variables including the direction and significance of dependency ([Bryman, 2008](#_ENREF_7); [Neuman, 2011](#_ENREF_38)). Regression analysis shows how and to what extent certain changes in an independent variable can alter the dependent variable. It helps to define the conditional expectation of dependent variables when the independent variable is being specified. Therefore, linear regression analysis can be a prediction tool for the dependent variable, when predictor (independent) variable(s) is known. However, regression analysis does not perform optimally, when variables with small effect or causality are explored through observational data.

Two statistical functions indicate the goodness-to-fit of a regression model. The coefficient of determination, also known as R-squared (R2), indicates how well data fits a statistical model. In a linear regression model, R-squared equals to the square value of correlation coefficient (*r*) value (R2= *r*2). Therefore, R-squared may vary between 0 and +1 and closer R-squared values to +1 indicate higher goodness-to-fit of the model to the existing data.

The significance level of the model, also known as the *p*-value, reveals the consistency and validity of the model. The *p*-value is being compared to a threshold value, which is commonly suggested to be between 0.05 and 0.1 in social sciences ([Bryman, 2008](#_ENREF_7); [Neuman, 2011](#_ENREF_38)). The *p*-values less than 0.05 in regression analysis indicate that there is less than 5% chance that the two variables are not related. Thus when the *p*-value is smaller than 0.05, the regression model is considered as a reliable model to predict future scenarios with more than 95% validity.

## Canopy and surface cover reconstruction

Urban surface cover (i.e. outdoor surfaces up to the canopy of trees) were reconstructed via desktop extraction of visible land cover from Google Earth images. The proportional coverage of trees, grass, concrete, paving, asphalt, surface water, sand and vacant land in each public space was calculated via i-Tree Canopy V6.1. The i-Tree Canopy is a land cover estimation tool, being used by United States Department of Agriculture (USDA) Forest Service and is available at <http://www.itreetools.org/canopy>.

The i-Tree tool uses ESRI shape files and Google Earth maps to classify land cover surface materials. The land cover calculation in i-Tree Canopy is based on the supervised classification of sample benchmarks, selected randomly by the software. To evaluate the proportion of canopy cover in this case study, 100 sample points were classified in each public space. Due to the land cover class limitation in i-Tree Canopy (maximum six layers) public space features with similar thermal characteristics were grouped.

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# Research Outcomes and Contribution

The urban heat stress mitigation tools including cool surfaces, urban greenery and behavioural change are required to be revisited in a new perspective, which looks at the phenomenon from the eyes of space participants. In this context, the current research delivers:

* An integrated method to collect appropriate urban microclimate data based on aerial and hand-held thermal photography, contextual measurements and direct observational
* Heat resilience measures in public spaces of Australian cities
* An index for spatial heat resilience in public space
* Four peer-reviewed conference papers and three peer-reviewed journal publication in addition to final thesis

The UHI effect is a well-known and much researched feature. Important is therefore the particular focus of this study on social aspects and behaviour in public space during heat stress. The current research will expand our understanding about the probable influences of climate change on residents’ well-being in public spaces; including the question for better design codes for outdoor public spaces that are more resilient to heat stress.

# Thesis findings summary

‘Public life changes constantly in the course of the day, week, month and over a year’ ([J. Gehl & Svarre, 2013, p 12](#_ENREF_22)). Nevertheless, the complex interaction between public space and public life supports diversity, flexibility and adaptability of local communities and their outdoor activities ([Lin, 2009](#_ENREF_32); [Marialena Nikolopoulou, 2011](#_ENREF_42); [Stathopoulos et al., 2004](#_ENREF_56)). This case study supports the concept that urban microclimates influence public life by altering typology, duration, and frequency of outdoor activities in heat stress scenarios. Studying the dynamics of thermal discomfort in the current case study indicates that:

* The neutral thermal thresholds (NTT) for heat sensitivity in the studied public spaces vary from 28°C to 32°C.
* Optional activities (i.e. sitting, standing, eating, playing and sport) are highly sensitive to heat stress and start to decrease after the public space reached its NTT.
* Necessary activities (i.e. walking between home and work or for daily shopping) have more resilience to heat stress and start to decline after higher NTTs compared to optional activities especially in public spaces with more diversity of functions and supportive land use.
* Necessary and optional activity patterns are dependent on shading effect during heat stress conditions
* Social activities (i.e. group activities, cultural activities such as music playing) are more sensitive to time and organisational adjustments than heat stress, nevertheless, still follow necessary activities thresholds.
* Activity patterns in public spaces with more urban greenery and shadow coverage are more resilient to heat stress compared to hard-landscaped areas.

With a better understanding of the relationship between urban space, microclimates and public life, it is possible to develop prototypes of public spaces that respond to both functional demands and local microclimates ([Lehmann & Thornton, 2015](#_ENREF_30)). Urban greenery and shadow coverage can facilitate more diverse and extended activities in public space especially at higher temperatures. Thus, an increase in the tree canopy, softer landscapes and shadow coverage are suggested to achieve higher spatial heat resilience (SHR) in public space. Increased greenery leads to improved thermal comfort, which increases resilience to heat stress. Thermal load on outdoor participants decreases in heat resilient public spaces, resulting in more vibrant and healthier public life in cities.

Research findings propose heat resilience as a quality indicator for public space and support the application of urban greenery to make cities more resilient to heat. The neutral thermal threshold (NTT) is the suggested benchmark for public life vitality assessment at high temperatures since it indicates the extent of public life resilience to heat stress. In the context of climate change, heat resilience in public space can support more vibrant, healthy and safer urban environments in existing and future cities. Such spatial heat resilience supports the usability of outdoor spaces by local communities in hot scenarios.

# Research Limitations and Further Opportunities

This research is based on observational data and spatial microclimate measurement. It also focuses on a limited number of public spaces in Adelaide, Melbourne and Sydney. Further research can include more public spaces to increase the ability to generalise the results. Also, public spaces in other cities are the subject of further analysis via a similar method as people responses to urban microclimate are highly contextual. The use of radiant temperature in thermal discomfort calculation is another opportunity for further research.

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