Exploring the Relationship between Design and Outdoor Thermal Comfort in Hot and Dry Climate

by

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ABSTRACT

Moderate physical activity, such as walking and biking, positively affects physical and mental health. Outdoor thermal comfort is an important prerequisite for incentivizing an active lifestyle. Thus, extreme heat poses significant challenges for people who are outdoors by choice or necessity. The type and qualities of built infrastructure determine the intensity and duration of individual exposure to heat. As cities globally are shifting priorities towards non-motorized and public transit travel, more residents are expected to experience the city on their feet. Thus, physical conditions as well as psychological perception of the environment that affect thermal comfort will become paramount. Phoenix, Arizona, is used as a case study to examine the effectiveness of current public transit and street infrastructure to reduce heat exposure and affect the thermal comfort of walkers and public transit users.

The City of Phoenix has committed to public transit improvements in the Transportation 2050 plan and has recently adopted a Complete Streets Policy. Proposed changes include mobility improvements and creating a safe and comfortable environment for non-motorized road participants. To understand what kind of improvements would benefit thermal comfort the most, it is necessary to understand heat exposure at finer spatial scales, explore whether current bus shelter designs are adequate in mitigating heat-health effects, and comprehensively assess the impact of design on physical, psychological and behavioral aspects of thermal comfort. A study conducted at bus stops in one Phoenix neighborhood examined grey and green infrastructure types preferred for cooling and found relationships between perception of pleasantness and thermal sensation votes. Walking interviews conducted in another neighborhood event examined the applicability of a framework for walking behavior under the stress of heat, and how differences between the streets affected perceptions of the walkers. The interviews revealed that many of the structural themes from the framework of walking behavior were applicable, however, participants assessed the majority of the elements in their walk from a heat mitigation perspective. Finally, guiding questions for walkability in hot and arid climates were developed based on the literature review and results from the empirical studies. This dissertation contributes to filling the gap between walkability and outdoor thermal comfort, and presents methodology and findings that can be useful to address walkability and outdoor thermal comfort in the world's hot cities as well as those in temperate climates that may face similar climate challenges in the future as the planet warms.

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INTRODUCTION

Introduction

This dissertation addresses outdoor thermal comfort in hot and dry climates. A better understanding of how individuals experience heat on the streets will contribute to ensuring livability and resilience of cities in the conditions of rising temperatures and prolonged periods of heat. Drawing from the fields of biometeorology, urban design, and behavioral sociology, this study is an interdisciplinary attempt to understand how design affects the thermal comfort of stationary individuals; explore how built infrastructure and landscapes affect the thermal comfort of walking pedestrians; and test the compatibility of outdoor thermal comfort and walkability frameworks for hot and dry climates. To fulfill these objectives, this dissertation relies on two overarching frameworks. The first implies that infrastructure is a product of the interactions of social, ecological and technological systems (SETs). Thus, a SETs lens has to be adopted when developing strategies to increase resilience of cities to intensifying weather extremes (Markolf et al., 2018). This study has emerged as a part of a large project Urban Resilience to Extremes Sustainability Research Network, connecting scientists and practitioners to address resilience to extreme events in ten cities across the U.S. and Latin America using the SETS framework ("Home - UREx Sustainability Research Network," 2019). The second is based on the assumption that people adapt to the environment to minimize discomfort. The adaptive model of thermal comfort includes three aspects: physiological, psychological and behavioral/physical (Nikolopoulou & Steemers, 2003; Rupp, Vásquez, & Lamberts, 2015). This framework emphasizes that subjective perceptions of the environment are equally important as objective ones. Therefore, this dissertation aims to study the effect of both subjective and objective domains on outdoor thermal comfort.

This chapter provides and introduction to the study and an overview of the scientific literature that sets up the context for this work. First, it gives an overview of the environmental variables influencing physiological thermal comfort and describes psychological aspects of thermal. Then, implications of non-motorized mobility and heat exposure are discussed. Furthermore, the case study of Phoenix and specific study sites are introduced. The last section presents descriptions of the three main chapters.

Environmental variables affecting physiological factors of thermal comfort

Fanger (1972) developed the first concept of thermal comfort. He defined it is as 'the human satisfaction with its thermal environment'. His definition is based on the energy balance between the human body and the environment. Fanger identified that the person will feel comfortable if the body is in heat balance, and the sweat rate and the mean skin temperature are within comfort limits. Environmental variables that affect thermal comfort are ambient temperature, radiant temperature, humidity, and air movement; behavioral variables include metabolic rate and clothing (Fanger, 1972).

<u>Climate change effects on environmental variables</u>

Climate change has and very likely will continue to have a substantial impact on the mentioned above environmental variables. Human activities have already increased the global average air temperature by 1°C since the industrialization and the temperature continues rising at 0.2°C per decade (IPCC, 2014a). We have already witnessed the outcomes of temperature rise: higher surface temperatures, more frequent heatwaves, increase in heavy precipitation and droughts in some locations. Further warming is projected to cause major changes in temperature extremes, further increases in runoff and flood hazard, sea level rise, and hinder efforts to reduce air pollution (IPCC, 2014a). Climate change does not influence all areas in the same way. The Southwest is one of the most 'climate-challenged' areas of the U.S. Arizona is already one of the hottest and driest areas in the country. The average daily temperatures were the highest in the 2000s and continue rising. Both maximum and minimum temperatures are increasing, with the latter increasing more rapidly as a consequence of urbanization. Scientists predict that warming will continue with hotter summers and falls, longer and hotter heat waves, higher temperature extremes, increases in surface temperatures and more severe droughts. According to climate projections, one in 20 years extreme heat days of the last century will occur every two or three years nationwide by the end of this century ("Full Report | National Climate Assessment," 2014). Mean air temperatures are likely rise up to 5°C by 2100 based on high emission scenario. Those changes will drive increased heat morbidity and mortality with disadvantaged population affected the most (Garfin, Jardine, Merideth, Black, & LeRoy, 2013).

Less winter and spring precipitation is projected for the Southwest of the country. Changes in wind patterns are uncertain ("Full Report | National Climate Assessment," 2014).

Effect of design strategies on environmental variables

Design strategies can influence environmental variables on the local scale. As mentioned above, air temperature, short and long wave radiation, humidity and wind are the main variables that influence thermal comfort.

Air temperature is the most commonly used parameter to assess urban climate (Lenzholzer, 2015), even though there is a growing body of literature suggesting that it has limited influence on the thermal comfort (Emmanuel & Fernando, 2007; Klemm, Heusinkveld, Lenzholzer, & van Hove, 2015; Krüger, Minella, & Matzarakis, 2014; Middel, Selover, Hagen, & Chhetri, 2016). Changes in air temperature on a microscale are not significant, and thus, urban design interventions have a small effect on the air temperature. However, when several measures are combined together, the effect can be much greater (Lenzholzer, 2015). Variations in air temperature are more noticeable on a larger city scale in comparison to rural areas. Higher air temperatures are often observed in dense urban cores with high amount of impervious surfaces, and are known to create the urban heat island effect (Oke, 2011). Nevertheless, higher air temperature may not result in higher thermal discomfort. The body exchanges heat through radiation and convection, thus, higher convection load may be less significant than reductions in radiative load due to more shading from buildings (Erell, Pearlmutter, & Williamson, 2011).

Shortwave radiation from the sun and longwave radiation from the surrounding surfaces have high a impact on thermal comfort. It is usually reflected in the globe temperature or mean radiant temperature. Globe temperature is defined as a temperature inside a black copper globe ("Kestrel. User Guide. Kestrel Heat Stress Tracker," n.d.) and combines the effects of air temperature, radiant temperature and wind. Mean radiant temperature (Tmrt) only measures radiant exposure and is defined as "uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non- uniform enclosure" ((ISO), 1998; Middel & Krayenhoff, 2019). Sun and shade greatly affect globe temperature and Tmrt. Thus, design with solar exposure and shade patterns in mind can substantially influence pedestrian thermal comfort. Buildings and shade structures change shading patterns in different ways. Shade can be provided by controlling the sky view factor (SVF), height to width (H/W) ratio, street orientation and building configuration as well as planting trees and installing structural shade. Material properties such as albedo, surface roughness and emissivity significantly influence the amount of radiation emitted by the surfaces (Erell et al., 2011; Lenzholzer, 2015).

Humidity combined with high temperatures can have a negative impact of thermal comfort. The air is saturated with water vapor and cannot absorb the sweat. Humidity is also relatively uniform and difficult to influence on a small scale (Lenzholzer, 2015). In hot and dry climates, like Phoenix, rising humidity can positively affect thermal comfort by lowering the air temperature and increasing convective cooling of the body. Vegetation and trees positively affect humidity levels (Erell et al., 2011). Mechanical devices, such as misters and cooling towers are also popular measures in hot and arid climates.

Wind is another factor that affects thermal comfort. Air movement increases the rate of sweat evaporation and helps to cool the body. However, it can also affect the mixture of air masses and weaken the differences in microclimate. High winds can be uncomfortable. Wind patterns can be affected by H/W ratio, building and street orientation in relation to prevailing wind direction, and by planting trees (Erell et al., 2011; Lenzholzer, 2015).

Observed or modeled effects of urban design on environmental variables

Observed and modeled effects of design strategies on the described environmental variables from scientific literature will be further explored. This overview will concentrate on the summer months of the hot and arid climates similar to Phoenix, Arizona. This overview will set up the context for empirical studies in Chapter 2 and 3. A study conducted in the semi-arid Constantine City in Algeria examined street canyons with varying H/W ratios (between 1 and 4.8) and SVF's (between 0.076 and 0.58). Authors found a varying degree of influence of SVF on air temperature throughout the 24-hour period. The effects were significant between 12 am and 6 pm, but similar temperatures were observed between 6 pm and 4 am. Overall, street canyons with higher H/W ratios and smaller SVF were cooler at peak daytime temperatures with up to 6°C difference. Surface temperature differences were even higher (up to 12°C) and showed higher correlation with SVF (Bourbia & Boucheriba, 2010).

Crewe at al. (2016) conducted measurements at seven different sites along the Ash and Mill Avenues, University Avenue, corridor walkways at Arbor Walk and Tunnel, and areas with the arcade and overhangs in Tempe, Arizona. These streets exemplify a wide range of designs, from typical Southwestern wide and exposed streets to shadier streets, recently remodeled according to the New Urbanism principles. Authors found that sun exposed areas with high SVF were cooler at night and hotter during the day, with morning air temperatures of 29.7°C and 41.9°C at noon, shaded sites were between 28.6°C in the morning and reached 40.4°C at noon in summer. The globe temperature for summer was much higher, 35.7–34.5°C in the morning 56–55°C at noon for streets with high SVF, and 28.2–30.9°C and 42.1–53.5°C for low SVF. To assess the impact of the temperature on human comfort, the authors calculated PET index (Physiological Equivalent Temperature), which is defined as the air temperature at which the human body is usually at heat balance indoors and compared to outside conditions. Sun exposed Ash and University Avenues had extremely high PET values and remained very hot for the longest period, while other streets with lower SVF and various design principles were also very hot, PET values did not reach the extremes and higher temperatures lasted for shorter time during the day (Crewe, Brazel, & Middel, 2016).

Ali-Toudert and Mayer (2006, 2007) modeled the effect *of street orientation* and H/W ratio on temperatures in Algeria with hot and dry climate. They found that north-south streets have lower and shorter periods of high PET values and increased H/W has a positive effect on shading. In contrast, H/W has minimal effect on east-west oriented streets. Galleries along the east-west oriented streets were effective in reducing sun exposure and improving thermal comfort. Trees decreased the PET by 22K under the tree crown (Ali-Toudert & Mayer, 2006, 2007).

Spatial configurations of buildings and amount and type of vegetation can significantly affect environmental thermal comfort variables. Middel et al. (2014) examined the most common spatial and landscape arrangements for Phoenix, Arizona, such as open low-rise, open midrise, compact low-rise, compact midrise, and compact high-rise in combination with mesic (trees and grass), oasis (soil, grass patches, trees and shrubs), and xeric (desert style vegetation) landscaping. She found that open scenarios with higher SVF are warmer in most cases. Compact high-rise scenario was the coolest, reinforcing the positive impact of low SVF and high H/W ratio on cooling and improved thermal comfort. Mesic sites with grass were the coolest and xeric were the hottest.(Middel, Häb, Brazel, Martin, & Guhathakurta, 2014)

Trees and vegetation are effective in reducing air and radiant temperature, increasing humidity and effecting wind flow. Large to medium size parks create a park cool island phenomena: parks are cooler in comparison to nearby areas. The magnitude and time of cooling depends on the park size, amount of irrigation and type of ground cover and wind direction. Smaller parks also show moderate cooling effects. The cooling effect of trees depends on the type and size of the tree, leaf density, and irrigation patterns. Trees limit incoming solar radiation and reduce the absorbed radiation of the ground surface by casting shadows (Erell et al., 2011).

Psychological factors of thermal comfort

Nikolopoulou & Steemers (2003) suggest that psychological adaptation is influenced by several factors: naturalness, expectations, short and longterm experience, time of exposure and perceived control over the environment. Some of those parameters characterize the environment, and others are related to individual experiences.

Naturalness relates to the degree of artificiality in the environment. Research shows that people can better tolerate changes that are produced naturally. *Expectations* determine what the environment should feel like in relation to the season or previous days.

*Experienc*e influences the expectations. Short-term experience is influenced by day to day changes in weather. Long-term experience is influenced by the schemata of actions constructed in the brain in relation to the environmental conditions. *Time of exposure* may change the perception of thermal comfort. Short exposure to uncomfortable conditions is less likely to be perceived negatively. People feel more comfortable when their *perceived control* over the environmental situation is higher. Authors showed that people who had a choice between sun and shade reported higher thermal comfort levels even though they did not adjust their position. Similarly, people who had to be in a particular place, for example waiting for someone, felt less comfortable than people who chose to be in that place for other reasons. (Nikolopoulou & Steemers, 2003).

Knez et al. (2009) developed a model of influence of physical place and weather related parameters on human response (Fig. 1). It incorporates physiological, psychological and behavioral factors. The model consists of three elements: place, moderator/mediator, and human response. Place encompasses actual physical form as well as its environmental characteristics, mediating factors are related to the individual physical and demographic characteristics, emotional state, expectations and cultural norms that enable to evaluate a space in a certain way and to generate a response in a form of adaptation, coping behavior or particular emotion (Knez, Thorsson, Eliasson, & Lindberg, 2009).

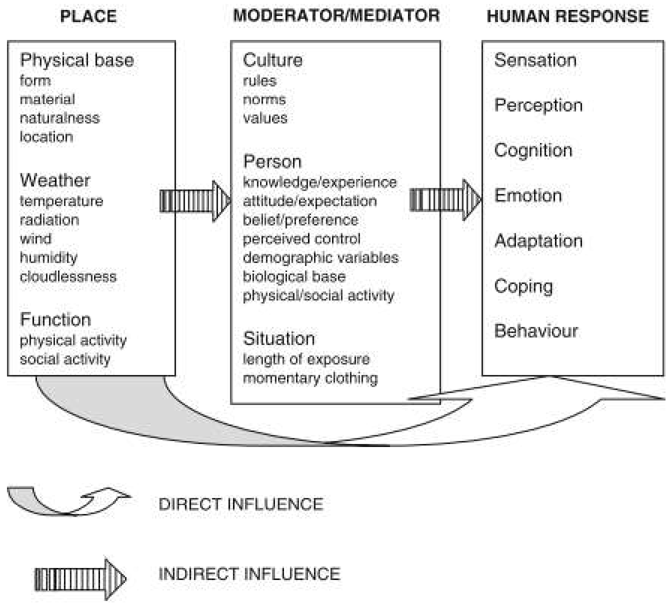


Figure 1
Proposed direct and indirect (via moderator/ mediator) influences of a place on a person (human response) (Knez et al., 2009)

Observed effects psychological factors on thermal comfort

Nikolopoulou & Steemers studied the use of outdoor places in Cambridge, UK. They found that the calculated predicted mean vote (PMV), index developed by Fanger for thermal comfort assessment based on the metabolic activities, clothing and environmental parameters (Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016; Fanger, 1972), significantly differed from the subjective evaluation of thermal comfort by the study participants. Microclimate properties of the environment accounted for 50% of the variation in the responses, and the authors attribute the rest to the psychological factors discussed above (Nikolopoulou & Steemers, 2003).

Middel et al. examined the effect of shade on perception of heat at the pedestrian walkway at Arizona State University. The authors found that globe temperature was the only significant environmental predictor of thermal comfort and explained 51% of reported thermal sensation votes. Other significant factors were adaptation, thermal comfort vote, thermal preference, gender, season, and time of day. Moreover, they found that participants in the sun tended to overestimate air temperature, while participants in the shade underestimated, which exemplifies the effect of expectations. Shade improved thermal comfort by one point on a thermal comfort scale except for the winter. They calculated the acceptable comfort range between 19.1 °C– 38.1 °C, which is much higher than in temperate climates and shows the effect of acclimatization (Cohen, Potchter, & Matzarakis, 2013). Participants who were in the air conditioned buildings five minutes before the survey felt more comfortable at high temperatures showing the importance of previous experience (Middel et al., 2016; Nikolopoulou & Steemers, 2003).

The effect of the physical environment on physiological and psychological aspects of thermal comfort is complex. One can weaken or reinforce the other, and thus, it is difficult to separate for example the physiological effect of the tree on human body from its influence on the mind. Moreover, the study of psychological adaptation is still in its infancy and there are no methods to quantitatively evaluate the effect of individual psychological factors (Nikolopoulou & Steemers, 2003).

Nevertheless, empirical evidence shows that psychological adaptation is an important component of the overall thermal comfort. Carefully selected design strategies can influence several psychological components related to the physical space. Most of the strategies will also have an impact on physiological thermal comfort.

Naturalness can be affected by adding different types of vegetation and natural materials to the area (Klemm et al., 2015; Nikolopoulou & Steemers, 2003). Klemm et al. found that streets with combined trees and gardens were perceived as more comfortable than streets with only trees during hot summer days, even though streets with only trees had lower Tmrt values. This can be attributed to the fact that people valued variability in design. Streets without greenery were perceived as least comfortable and were in accordance with actual Tmrt values (Klemm et al., 2015). In the case of heat, use of materials and colors that are perceived as 'cold' will positively impact psychological aspect of thermal comfort (Lenzholzer, 2015).

Short-term experiences can be influenced by a holistic approach to planning and design of city blocks and streets. Changes in zoning regulations to increase density, diversify uses and urban form, changing building setbacks, adding arcades and shading devices, capturing breezes with proper building configurations would offer a wider variety of both visual and thermal stimulations, opportunities to switch between the indoor and outdoor, have more control of the environment and alter time of exposure to comfortable levels. Diversifying streets, bust stops and resting places by offering several types of microclimates in the sun and shade would give more perceived control over the environment and impact physiological and psychological thermal comfort. (Nikolopoulou & Steemers, 2003). The effect of psychological perceptions on thermal comfort is empirically tested in the following two chapters.

Non-motorized mobility and heat exposure

Since the main body of this work concentrates on outdoor thermal comfort, non-motorized mobility and use of public transit are important necessary activities that can result in additional exposure to heat. This section provides an overview of the literature related to the challenges of heat exposure of public transit riders in the hot climates. Currently, low-income and marginalized communities use public transit and engage in non-motorized transit activities more often than other users (Karner, Hondula, & Vanos, 2015).

For vulnerable populations that do not have access to air conditioning inside their homes, exposure to heat due to transit related activities can be a critical component that adds to total exposure (Karner et al., 2015). Riders' exposure is characterized by two factors: a walk time to the stop and the wait time at the stop. Estimated walking time in the area serviced by the Regional Public Transportation Authority ranges from 1.9 to 9.9 minutes and increases with lower density. The waiting time at the neighborhood stops averages 9.0–14.1min in the Valley Metro service area. The highest frequency routes are connecting major activity centers and longest waiting times are along non-arterial roads and at the fringe developments (Fraser & Chester, 2016). In addition, individual perception of time may substantially differ from the objective time. Public transit infrastructure is usually negatively associated with the waiting time and transit users usually perceive time spent waiting at the transit stop as significantly longer as it actually is. This phenomenon is usually expressed as a waiting time multiplier, a ratio of perceived waiting time to the actual waiting time or the time spent in a transit vehicle. A study by Fan et al. (2016) found that bus stop characteristics can alter perceptions of the time and that basic amenities at stops help to reduce perceived wait time (Fan, Guthrie, & Levinson, 2016). The effect of heat on perceived waiting time is not explored, but it is sensible to assume that decreased thermal comfort may further increase perception of the wait time.

Case study of Phoenix

Phoenix, Arizona, located in the Sonoran desert, is used as a case study for this dissertation. Phoenix currently experiences about 110 days each year with the temperature above 38°C ("National Weather Service - NWS Phoenix," n.d.). Considering that most of the population growth will occur in areas with arid climate (Golden, 2004; Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006), Phoenix will serve as a showcase study to present methodology and findings that can be useful for the world's hot cities as well as those in temperate climates that may face similar climate challenges in the future as the planet warms.

Development history

Phoenix has rapidly developed during the second wave of U.S. urbanization that occurred in the last seventy years. The city developed at a growth rate of 45.3% per decade between 1920 and 2000 (Keys, Wentz, & Redman, 2007). The rapid growth of Phoenix after WWII determined its spatial pattern designed for the automobile. Widespread use of air conditioning and mass-production housing techniques together with predominant car use resulted in a city built with few considerations of local climate (Gober, 2006).

Due to its recent development, Phoenix does not have a history of Spanish and Mexican periods with strong cultural legacy unlike other cities in the Southwest. Thus, migrating Anglo populations have taken over the control of the city growth and development and created spatial rules that restricted people of color to the least desirable areas of the city, and limited their movement and use of public services. Historically, Mexican communities lived in barrios and ethnic neighborhoods and occupied the area from 16th Street to 24th Streets and Washington Street to the Salt River; and 2nd and 4th Avenues south of Washington Street. Most of them were firmly rooted by 1940's. When city decided to expand the Phoenix Sky Harbor Airport in 1970's in an attempt to boost economic development of defense manufacturing and tourism, they have selected the Golden Gate Barrio as an expansion site. Residents were dispersed to nearby low-income downtown urban areas without concern of preserving the social cohesiveness of the neighborhood. Sixteen hundred households were removed by 1986. Another major infrastructure change that severely affected inner-core neighborhoods and caused more relocations and segregation was construction of the two major freeways: I-17 in the 1970's and I-10 in the 1980's. Freeway construction lowered residential property values even further and by 1990's, 40% of residential land was transformed for industrial use (Bolin, Grineski, & Collins, 2005; Gober, 2006). The above mentioned historical patterns have shaped Downtown Phoenix to its current state: poor quality low-income neighborhoods dispersed between industrial sites with large parcels of vacant land and brownfields on the east and south and gentrifying urban core to the north.

Vulnerability to heat

Harlan et al. spatially applied the heat vulnerability index to census block groups for Maricopa County to derive neighborhood level vulnerability. Authors identified three main factors: socioeconomic vulnerability (combined with no air conditioning), elderly and isolation, and lack of vegetation. Their analysis did not include diabetes as one of the factors. Scientists found that downtown areas of Phoenix and Mesa are most vulnerable to heat (Harlan, Declet-Barreto, Stefanov, & Petitti, 2013). Furthermore Jenerette et al. discovered that there is a strong correlation between socio-economic variables and land surface temperature. Land surface temperature is driven by material properties such as conductivity, heat storage capacity, and thermal inertia and their spatial composition, such as percentage of vegetation, buildings and roads. They found a strong relationship between socio-economic factors and land surface temperature. Neighborhoods below poverty line were 22% hotter and had 20% less vegetation (Jenerette et al., 2015). Harlan et al showed that there can be up to 4°C temperature difference between the city neighborhoods in the summer and up to 6°C difference during the extreme heat events (Harlan et al., 2006).

Study sites: Edison Eastlake and South Mountain Village

South Mountain Village and Edison Eastlake neighborhoods are among the most vulnerable areas to heat morbidity and mortality and (Karner et al., 2015) and are some of the hottest neighborhoods in Phoenix due to the lack of vegetation, proximity of freeways, and differences in built infrastructure. Poor environmental and socio-economic conditions in Edison Eastlake and South Mountain Village are the result of the history of racial segregation and environmental injustice. Both neighborhoods are located within the high heat vulnerability index zone with 25% of heat related deaths between 2000 and 2008 (Harlan et al., 2013). Residents of these neighborhoods also rely on public transit more than the rest of the city. Not surprisingly, they are also the most socio-economically vulnerable with 67% of residents below poverty line in Edison Eastlake and 27% in South Mountain Village (Arizona Department of Health Services, 2018; *Edison Eastlake Community Health Impact Assessement*, 2017).

The Edison Eastlake neighborhood is surrounded by the I-10 freeway on the north and east. It has three public housing projects on site. Residents are predominantly Hispanic and African American. Many of the residents have existing health issues that can potentially increase their vulnerability to heat and most do not have a car. Educational attainment is low, with 71% of residents having a high school diploma or less (*Edison Eastlake Community Health Impact Assessement*, 2017).

South Mountain Village is located in the southern part of the city bounded by I-10 freeway on the east and I-17 on the north. This predominantly Latino and African American neighborhood is characterized by the disproportionate concentration of industries with the use of toxic chemicals and hazardous waste sites, and poor air quality as the result (Bolin et al., 2005). Acute respiratory infections are the leading diagnosis in the neighborhood. Similarly to Edison Eastlake, many residents do not own a car and rely on public transit. Educational attainment is also low, with 58% having a high school diploma or less (Arizona Department of Health Services, 2018).

Dissertation structure

This dissertation consists of three standalone studies about the interactions of design, outdoor thermal comfort and walkability. Chapter 2 examines current microclimate conditions and heat perceptions of public transit riders in South Mountain Village and how it is affected by the differences in bus-stop design. Chapter 3 explores the differences in thermal comfort and street perceptions of walking individuals in Edison Eastlake neighborhood. Chapter 4, tests test the compatibility of outdoor thermal comfort and walkability in hot and arid climate drawing from the literature and empirical studies from the above chapters and introduces guiding questions for design in hot and dry cities.

CHAPTER 2

IS THIS BUS STOP COOL? PUBLIC TRANSIT INFRASTRUCTURE AND HEAT PERCEPTIONS IN HOT AND DRY CLIMATES

Abstract

Many cities aim to progress towards their sustainability and public-health goals by increasing use of their public-transit systems. But in extreme climates, dangerous or very uncomfortable weather conditions may reduce use if transit-stop infrastructure fails to moderate riders' exposure to those conditions. We took micrometeorological measurements and surveyed riders about their perceptions of heat and heat-coping behaviors at six transit stops in Phoenix, Arizona during the summer of 2018. We identified the infrastructure elements and coping behaviors that made riders feel cooler. We found that aesthetically pleasing stops were rated as more thermally comfortable than stops rated as less pleasant. Findings indicate that current infrastructure standards and material choices for bus stops in Phoenix are inadequate to provide thermal comfort, and can even contribute to hotter microclimates. We concluded that cities wanting to increase public-transit use should prioritize thermal comfort and multi-functionality when designing public-transit stops.

Hot town, summer in the city[1]

It is close to noon and 40°C out. There is not a single cloud in the sky to offer at least a temporary relief. The concrete is so hot that you can feel it burning your feet through your shoe soles. Several people at the bus stop hide in the strip of shade behind the shade structure, which feels as hot as an iron. Others find respite in the wisp of shade from a light pole. Constantly looking for shade here becomes a survival instinct. This is a typical Phoenix summer day.

The majority of studies on extreme heat exposure use air temperature, wind and humidity measurements from few weather stations to estimate the exposure of a certain population group. This data does not reflect the variety of microclimate conditions created by differences in the urban landscape experienced by people on the ground (Kuras et al., 2017). Furthermore, review papers on thermal comfort have concluded that thermal comfort is a complex phenomenon that is influenced not only by physiological body response to climate stressors, but also by psychological, behavioral, social, and cultural factors. Thus, models based solely on physical climate characteristics cannot adequately predict how individuals perceive thermal comfort (Chen & Ng, 2012; Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016; Djongyang, Tchinda, & Njomo, 2010; Rupp, Vásquez, & Lamberts, 2015; Vanos, Warland, Gillespie, & Kenny, 2010). Evidence suggests that physical conditions explain up to 50 percent of variations in thermal comfort; the remaining half is attributed to psychological, behavioral, social, and

[1] The Lovin' Spoonful - Summer In The City (1966)

cultural factors (Middel, Selover, Hagen, & Chhetri, 2016; Nikolopoulou & Steemers, 2003).

Nikolopoulou and Steemers (2003) suggest that psychological adaptation to climate is influenced by several factors: presence of natural elements in the environment, expectations of climate conditions in relation to a particular season or previous days, time of exposure to outdoor conditions, and availability of microclimate alternatives that give the user perceived control of the environment. However, to our knowledge, there is still no research on the relationship between urban design, aesthetic preferences and outdoor thermal comfort.

Walkability and transportation literature suggests that certain design qualities of built structures and street amenities can incentivize walking, promote social activities, and reduce perceived waiting times at transit stops (Ewing & Handy, 2009; Fan, Guthrie, & Levinson, 2016; Gehl, 2011; Jacobs, 1961; Mehta, 2007). In this study, we aim to examine the effect of built infrastructure and landscaping on heat perception of the bus risers. Public-transit riders are exposed to heat while walking to and waiting at the bus stop.

A testbed for heat

A desert city of Phoenix, Arizona, is used as the case study. Phoenix is located in the Sonoran desert, and is one of the hottest cities in the country experiencing about 110 days during which maximum daily temperatures exceed 38 °C ("National Weather Service - NWS Phoenix," n.d.). Since extreme heat is a growing problem in many cities,

one that results not only in discomfort, but sometimes in illness and death (IPCC, 2014), Phoenix is used as a testbed to learn how modern cities can address urban heat.
In the Phoenix metropolitan area, average exposure is in the range of 13 to 21 minutes, and it increases at urban fringes (Fraser & Chester, 2016). Being outdoors that long when it is over 38°C is uncomfortable, and potentially dangerous. What can cities do to protect public-transit users from extreme heat? This chapter will concentrate on the rider's exposure while waiting for the bus, and the next one will address thermal comfort of walking pedestrians.

Phoenix is projected to double its population in the next 30 years, a common challenge for many metropolitan areas. The city's Transportation 2050 Plan aims to support population growth by improving conditions for non-motorized mobility and public transit use ("Phoenix transportation 2050 Plan Overview," n.d.). To make sure that proposed infrastructure changes effectively mitigate heat extremes and provide thermally comfortable conditions for public-transit users, we need to understand not only what thermal conditions current infrastructure provides, but also how it affects users' perception of thermal comfort.

To learn more about how transit stops (which are one kind of urban design element) influence the physiological, psychological, and behavioral components of thermal comfort, we examined how bus-stop infrastructure affected thermal conditions and thermal comfort of waiting riders at Phoenix bus stops during the summer of 2018. We measured thermal conditions, identified which infrastructure and natural elements riders perceived to have cooling benefits, and analyzed how riders' perceptions of stop aesthetics influenced their thermal comfort. Our findings contribute to understanding of how personal thermal comfort is affected by urban infrastructure elements while performing daily activities. Our results provide details on how infrastructure design and landscaping elements perform for thermal comfort in conditions of extreme heat. We argue that by implementing small changes in built form and integrating natural elements, urban designers can improve how comfortable individuals feel outdoors, even in extreme heat.

Methods

We measured air and globe temperature, wind, humidity, and surveyed riders at bus stops. Relationships between infrastructure, microclimate conditions, and riders' perceptions were explored using descriptive statistics, and linear and ordinal regression models.

Study sites

This study was done in South Mountain Village in Phoenix. South Mountain Village is a predominantly Latino neighborhood where poverty rates exceed 40% in some neighborhood tracts. The neighborhood has low car ownership compared to the rest of the city, and relies on public transit. In addition to socio-economic vulnerability, the neighborhood has high vulnerability to heat due to lack of vegetation, increased building density, high concentration of impervious surfaces, and limited access to AC in residents' houses (Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Harlan, Declet-Barreto, Stefanov, & Petitti, 2013).

We selected bus stops based on variability in bus-shelter designs differences in landscaping and average daily ridership. Standard, advertising, and art bus-stop shelter types (Fig. 2) are the types of bus-stop infrastructure in Phoenix, with standard and advertising shelters being predominant. A *standard* bus stop is made out of painted metal with a solid canopy, perforated back and side panels, and perforated metal bench. *Advertising* bus stops are similar in material and shape to standard, but have a triangular, solid advertising panel on one side. *Art* bus stops consist of a polycarbonate canopy with integrated artwork, several metal benches and individual seating. Entwined metal trellis form a vegetated awning behind the stop. However, vine density is not consistent across the trellis structure, sparse or no vegetation patches are common. Trees and shrubs have been planted around the art stops.

Baseline Road in South Mountain Village has a number of art shelters, along with the two other types (Figure 2). That is why we decided to concentrate the study along this street. We selected two stops of each type, all of them facing north to control for the differences in sun position and shade patterns (Figure 3).

Figure 2
Bus-stop types used in the study: standard, advertising, art (N=6)

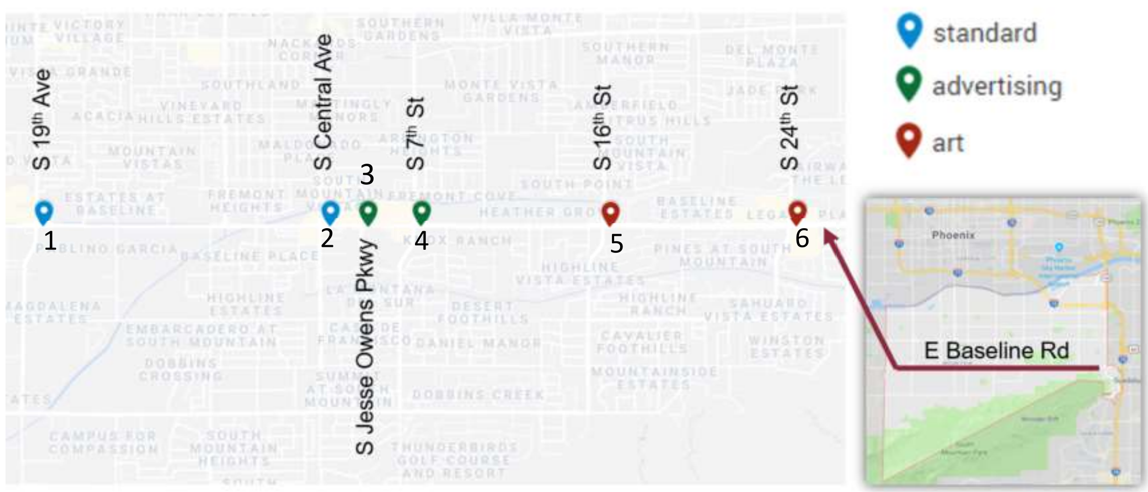


Figure 3
Bus-stop locations. South Mountain Village. Baseline Rd. (N=6)

The average daily ridership at the selected stops ranged from 29 riders a day at minor intersections, to 107 riders a day at major intersections (“Ridership Reports |

Valley Metro," 2019). These numbers are within the average for the region (Table 1), and thus current sample is a reasonable representation of the ridership conditions in Phoenix.

Table 1
Average daily ridership in Phoenix per bus stop April 2016 - June 2018

mean	**sd**	**min**	**max**	**median**
24.33	40.68	0	628	10.11

Study design and data collection

Meteorological measurements

We took measurements at different times of day and in a variety of sun and shade locations at each stop (see Table 2). Measurements were taken on 19 days between June 6 and July 27, 2018, on days with clear skies and maximum daily temperatures the in 38 – 43°C range. Because we wanted to compare microclimates between stops, we needed to remove the effect of day-to-day weather variations on microclimate variables. We did this by, for example, looking at differences between sun and shade temperatures at each stop, rather than at actual temperatures (i.e., we used differences in measurements rather than absolute values). We then averaged the differences for each microclimate variable at each stop, and compared the averages among stop types and times of day (all stops, morning, noon, and evening).

Table 2
Description of stop conditions, average daily ridership and surveys collected

Stop N	Stop ID	Number of collected surveys	Average daily ridership	Stop type	Sun (N)	Bus-stop shade (N)	Tree shade (N)	Vegetated awning shade (N)	Ad. sign
1	1004	9	29	St	Yes	Yes	No	No	No
2	62	24	70	St	Yes	Yes	No	No	Yes
3	68	6	30	Ad	Yes	Yes	Yes	No	No
4	42	9	35	Ad	Yes	Yes	No	No	Yes
5	40	18	36	Art	Yes	Yes	Yes	Yes	No
6	8063	17	102	Art	Yes	Yes	Yes	Yes	No

Ad. sign = Advertising sign

A team of two undergraduate students took measurements three times a day in two-hour intervals: 7:00-9:00 a.m., noon-2:00 p.m., and 3:00-5:00 p.m. These times were selected because they are the hours of peak ridership.

Kestrel 4400 Heat Stress Meters were used to measure air temperature, globe temperature, humidity, and wind speed. Surface temperatures were taken with IR thermometers, Extech IR260. Kestrel 4400 Heat Stress Meters were attached to tripods at a height of 1.1 m, which is the center of gravity of the standing human (Middel et al., 2016). All instruments complied with ISO 7726 standards for sensor measurement range and accuracy.

Surveys

Bus riders waiting at the stops were surveyed during the same time intervals during which meteorological measurements were taken. Requests to participate in the surveys were rarely declined. The survey took about five minutes to administer. Participants were offered cold water in appreciation of their time and effort. The limitation of this data collection method is that bus riders who arrived at the stop just before the bus arrived, or later than five minutes before the bus arrived, were not able to participate or complete the survey. After each survey was completed, survey administrators noted the respondent's apparent gender, sun exposure, and meteorological conditions at the stop (air temperature, globe temperature, wind speed, and humidity).

The survey (Appendix A) consisted of three parts. The first part asked riders how they typically got to the bus stop and how long it took them to get to there, how long they typically had to wait for the bus, what they did while waiting, and what their strategies were for coping with heat while waiting. The second part included questions about perception of the bus-stop infrastructure and thermal comfort. We asked about green and grey infrastructure elements that riders perceived to have cooling benefits. Questions in the second section were similar to those asked in a study by Knez et al. (2009). The last part included questions about riders' primary transit mode and vehicle ownership, the reason for the bus trip, income, and age. This project was approved by the Institutional Review Board of Arizona State University (STUDY00006309).

We used Spearman's rank-order correlation to identify relationships between responses to the survey questions and meteorological variables. Significant relationships were further explored in regression models. To ensure validity, we independently built linear and ordinal regression models for categorical (Likert-scale) variables.

Results

Microclimate conditions

We recorded 241 microclimate measurements at sun and shade conditions at bus stops (Table 3). Wind and humidity were not significant in influencing ambient and globe temperature. However, low humidity influenced low WBGT values, index that is commonly used to define heat safety standards by the Occupational Safety and Health Administration (OSHA) and the American Industrial Hygiene Association (AIHA)(Epstein & Moran, 2006). WBGT index is not optimal for hot and dry climates (Middel et al., 2016) and further analysis will concentrate on exploring the differences in the ambient and globe temperature.

Table 3
Range of microclimate variables during the measurement campaign between June 6 and July 27, 2018 (N=241)

Variable	mean	sd	min	max
Ambient T	39	4.1	28.4	45.8
Globe T	45.1	6.3	28.8	57.4
Wind	1.1	0.8	0	4.3
Humidity	18.1	12.1	5.4	62.6
WBGT	27.9	3.2	19.9	34.4

We used factorial ANCOVA to examine the effect of sun and various shade types on ambient and globe temperature. The model showed that shade significantly effects ambient temperature (R^2 =0.93) and globe temperature (R^2 =0.87). A stronger R^2 for the ambient temperature model was because ambient temperature from a local airport station was used as a covariate for both models and, thus, more strongly correlated with the model that predicts ambient temperature. Results showed that while all shade types were significantly affecting globe temperature, only trees and bus-stop shelters had a significant effect on air temperature.

To further understand the effectiveness of different shade types on reducing ambient and air temperature, we calculated and compared the differences between the sun and each shade type. To validate the method of using temperature differences instead of absolute values to control for day-to-day variations in temperature, we examined sensitivity of collected ambient temperatures and temperature differences (sun versus shade) to the hourly ambient temperature data from the local airport station. Ambient temperature from the Phoenix Airport Station was a significant predictor of measured ambient temperature (Figure 4), explaining 92% of variance. However, it was not a significant predictor of differences between sun and shade values (Figure 5). Thus, it can be implied that using temperature differences versus absolute values allows us to control for the day-to-day temperature variations and make comparisons between stops and infrastructure types sampled on different study days.

Table 4
Results for a factorial ANCOVA with ambient temperature as a dependent variable and local airport station ambient temperature as covariate; factors are sun and shade types available at the bus stop

Tests of Between-Subjects Effects					
Dependent Variable:		AmbientT			
Source	**Type III Sum of Squares**	**df**	**Mean Sguare**	**F**	**Sig.**
Corrected Model	3722.170[a]	5	744.434	602.769	.000
Intercept	38.911	1	38.911	31.506	.000
Phoenix Airport Station	3647.370	1	3647.370	2953.278	.000
Shade Type	47.041	4	11.760	9.522	.000
Error	290.231	235	1.235		
Total	372243.633	241			
Corrected Total	4012.401	240			

a. R Squared = .928 (Adjusted R Squared = .926)

Pairwise Comparisons						
Dependent Variable:			AmbientT			
					95% Confidence Interval for Difference[b]	
(I)Shade Type	**(J)Shade Type**	**Mean Difference (I-J)**	**Std. Error**	**Sig.[b]**	**Lower Bound**	**Upper Bound**
Sun	Tree	1.369*	.269	.000	.608	2.131
	Bus-stop shelter	.660*	.159	.000	.212	1.109
	Vegetated awning	.849	.337	.118	-.104	1.803
	Advertising sign	.842	.407	.332	-.308	1.992

*. The mean difference is significant at the .05 level
b. Adjustment for multiple comparisons: Sidak

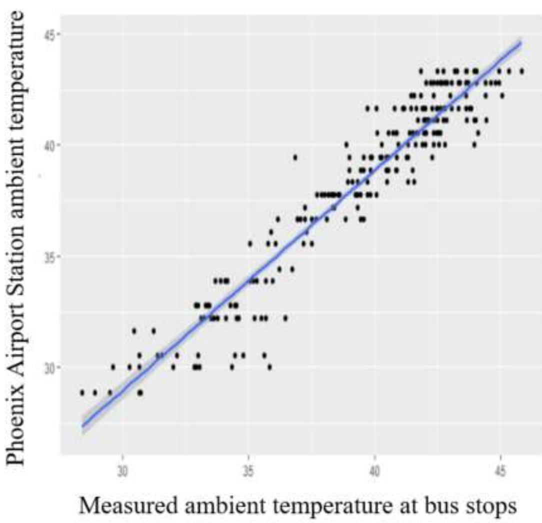
Table5
Results for a factorial ANCOVA with globe temperature as a dependent variable and local airport station ambient temperature as covariate; factors are sun and shade types available at the bus stop

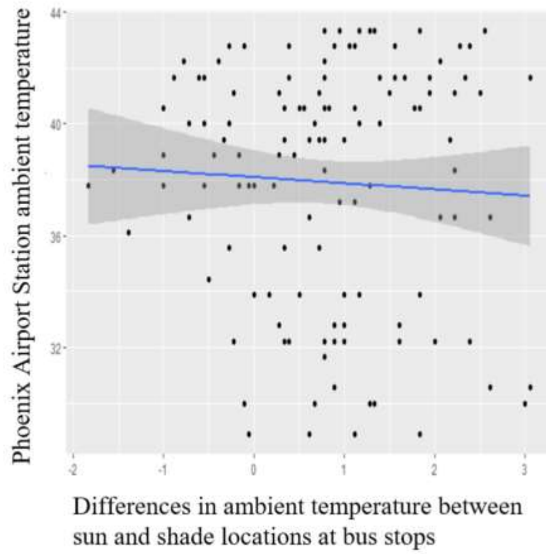
Tests of Between-Subjects Effects					
Dependent Variable:		AmbientT			
Source	**Type III Sum of Squares**	**df**	**Mean Sguare**	**F**	**Sig.**
Corrected Model	8288.148[a]	5	1657.630	316.315	.000
Intercept	62.310	1	62.310	11.890	.001
Phoenix Airport Station	4341.287	1	4341.287	828.421	.000
Shade Type	3834.887	4	958.722	182.947	.000
Error	1231.503	235	5.240		
Total	499697.019	241			
Corrected Total	9519.651	240			

a. R Squared = .871 (Adjusted R Squared = .868)

Pairwise Comparisons						
Dependent Variable:			AmbientT			
					95% Confidence Interval for Difference[b]	
(I)Shade Type	**(J)Shade Type**	**Mean Difference (I-J)**	**Std. Error**	**Sig.[b]**	**Lower Bound**	**Upper Bound**
Sun	Tree	8.452*	.555	.000	6.884	10.020
	Bus-stop shelter	7.975*	.327	.000	7.051	8.899
	Vegetated awning	6.237*	.695	.000	4.273	8.202
	Advertising sign	8.782*	.838	.000	6.413	11.150

Based on estimated marginal means
*. The mean difference is significant at the .05 level
b. Adjustment for multiple comparisons: Sidak





	Std. B	Std. Error	t value	P
(Intercept)	3.99823	0.69186	5.779	<.001
Phoenix Airport Station	0.92430	0.01811	51.032	<.001
R2: 0.9159				

Figure 4
Phoenix Airport Station hourly ambient temperature vs. measured ambient temperature at bus stops (N=241)

	Std. B	Std. Error	t value	P
(Intercept)	1.31756	0.83547	1.577	0.117
Phoenix Airport Station	-0.01288	0.02190	-0.588	0.558
R2: 0.002804				

Figure 5
Phoenix Airport Station hourly ambient temperature vs. differences in ambient temperature between sun and shade locations at bus stops (N=125)

Comparison of differences between various shade types (Figure 6) sampled at stops revealed that trees were most effective in reducing the ambient temperature (mean difference 1.3°C) and bus-stop shade was the least (mean difference 0.7 °C). Furthermore, ambient temperature under the bus-stop shade had the highest variability, including negative values, meaning that the ambient temperature under the bus-stop shade was higher comparing to no shade in some instances (Figure 7). We believe this can be attributed to high emittance properties of metal that stops are made of.

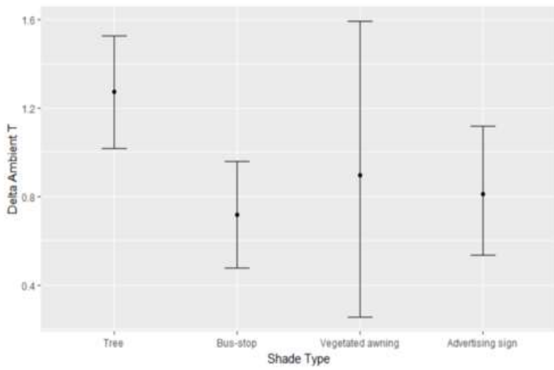


Figure 6
Average difference in ambient temperature per shade type (N=125)

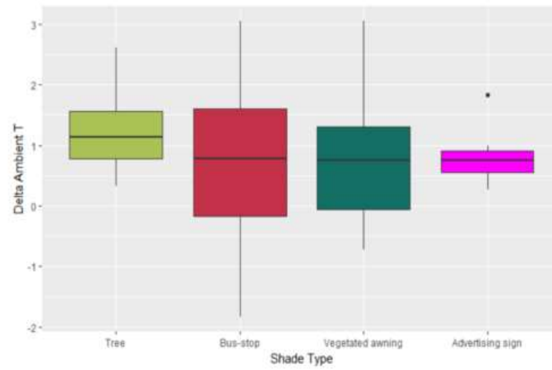
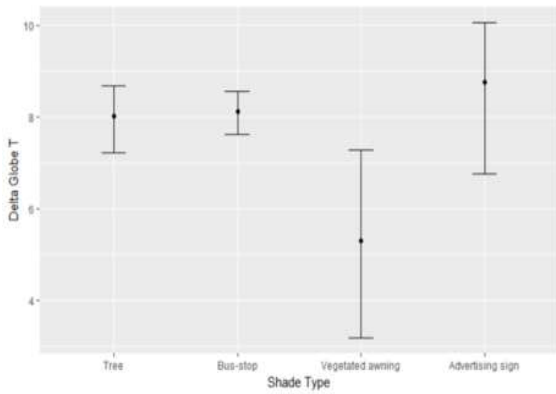


Figure 7
Boxplots of differences in ambient temperature per shade type (N=125)

Advertising sign, where people would often stand waiting for the bus, had the highest mean reduction in globe temperature of 8.8°C, emphasizing the effectiveness of solid vertical shade that is currently lacking. Trees (mean difference 8°C) and bus-stop shade (mean difference 8.1°C) performed similarly for reducing globe temperature (Figure 8). Vegetated awning was least effective (mean difference 5.3°C) and had the highest range of values (Figure 9). This was expected, since many of the vines at bus stops were not properly maintained and dried out not providing a lot of shade.



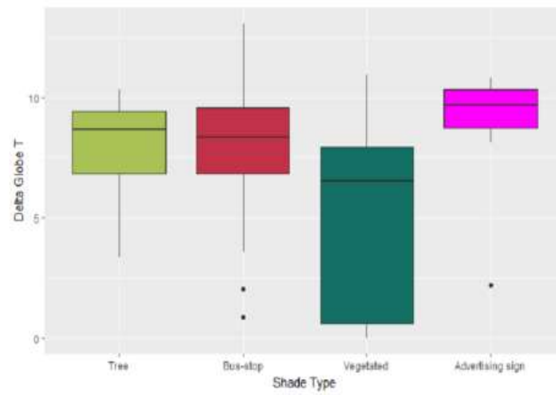


Figure 8
Average difference in globe temperature per shade type (N=125)

Figure 9
Boxplots of differences in globe temperature per shade type (N=125)

A closer exploration of differences between the bus-stop types showed that standard bus-stop shelter had the lowest impact on reducing ambient temperature (mean difference 0.2°C), with advertising bus-shelter having the highest impact (mean difference 1.1°C). Art bus-stop shelter had a mean cooling effect of 0.9°C and had the smallest range of values distribution (3.1°C) (Figure 10 and 11). One explanation to the highest reductions at advertising stops, was the solid vertical advertising panel on one side of the stop.

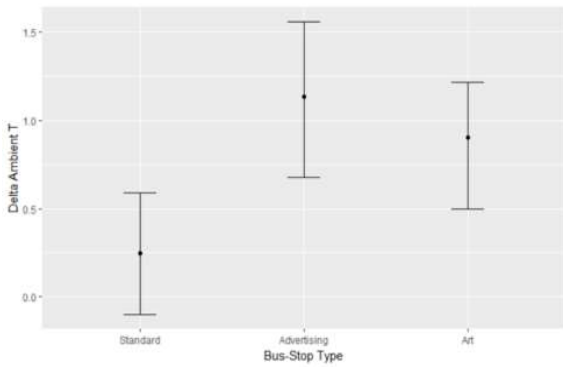


Figure 10
Average difference in ambient temperature per stop type (N=125)

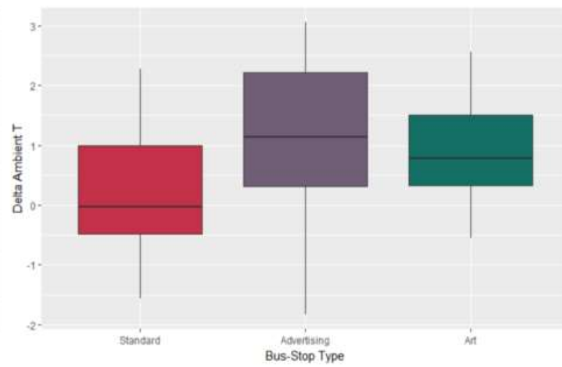
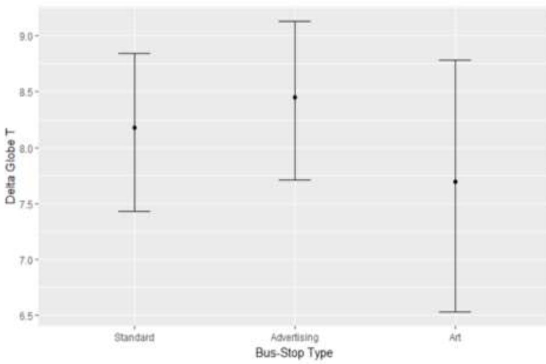


Figure 11
Boxplots of differences in ambient temperature per stop type (N=125)

In terms of globe temperature, standard and advertising bus-stop shelter types performed similarly, providing a mean cooling effect of 8.2 °C and 8.4°C respectively, with art stops having a mean difference of 7.7°C. One explanation to these differences is the difference in material properties and structure types. Based on visual examination, standard and advertising stops have solid metal roof, whereas art stop roof is made of a polycarbonate and had a higher light transmissivity, thus, allowing sun radiation to pass through. In addition, art stops did not have vertical panels.



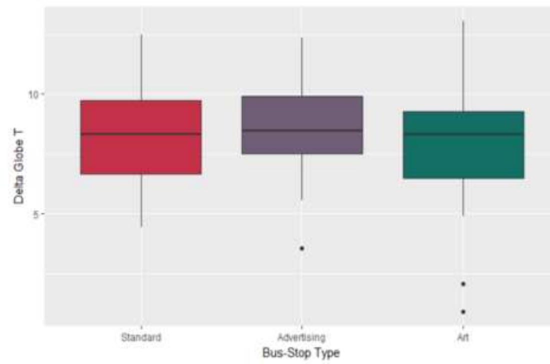


Figure 12
Average difference in globe temperature per stop type (N=125)

Figure 13
Boxplots of differences in globe temperature per stop type (N=125)

These results did not include the total area of shade provided at stops. For example, art bus-stop types had a larger shade structure, and, thus provided more shaded area overall comparing to standard and advertising stops, that provided slightly higher reductions in globe temperature, but more people often had to stand in the sun due to the lack of shaded area. In addition, standard and advertising stops did not provide combined effect of green and grey infrastructure in reducing ambient and globe temperature. For instance, trees that have shown to be effective in reducing ambient and globe temperatures were only available at art stops and on a nearby property close to one of the advertising stops.

Surface temperatures

We recorded 1003 measurements of surface temperatures of various material types available at the stops in sun exposed and shaded conditions (Figure 14). Materials include metal, concrete, dirt/gravel, asphalt and grass.

Asphalt was the hottest material with mean sun exposed temperature of 54.7°C and maximums over 65°C. No shaded values were available for the asphalt. Mean temperature for sun exposed metal bench seat is 39.7°C with the maximums above 60°C. Grass was the coolest material measured, with the mean of 38.4°C in the sun. Sun exposed values for all man-made material types included values sufficient for a skin burn at 5-seconds or 1-minute exposure (*ISO 13732,2010*). Shade lowered surface temperatures by as much as 20°C and neutralized the differences between material types with nearly all values falling below the skin burn thresholds.

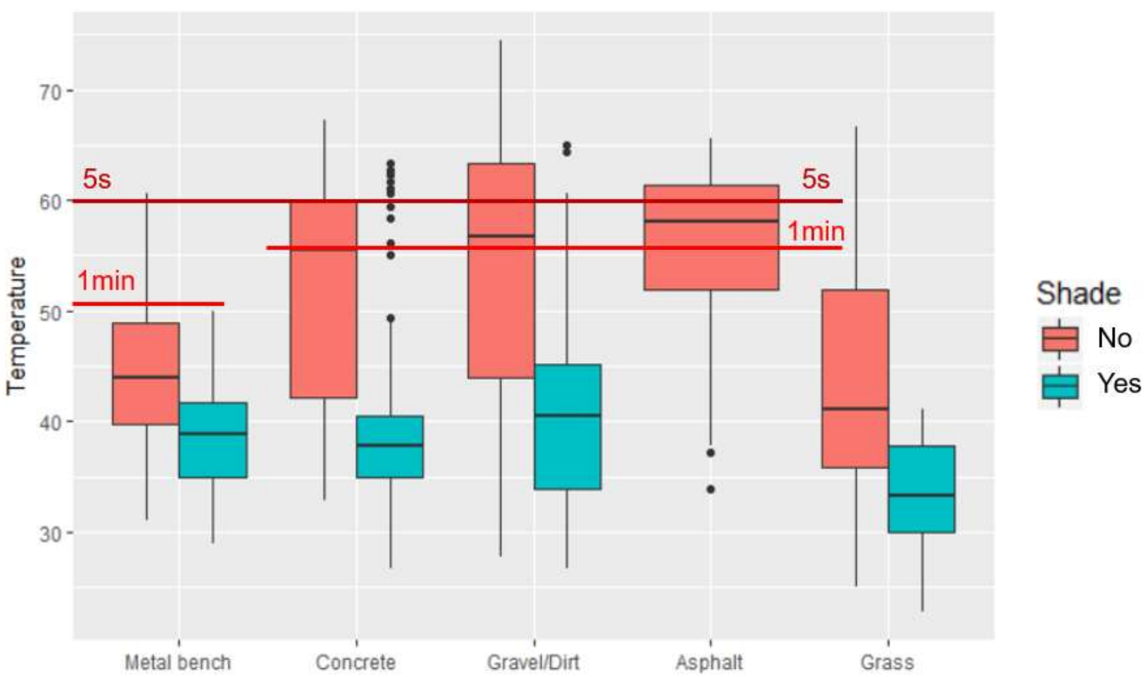


Figure 14
Boxplot of surface temperatures of available materials in the sun and shade with 5-seconds and 1-minute skin burn threshold (ISO 13732, 2010) (N=1003)

Surveys

During the study, we collected 83 questionnaires (Table 6) at three types of stops described above. Comparison of demographic information to the regional rider profile reflects disadvantaged conditions of the neighborhood comparing to Phoenix Metropolitan Area with 52% of the study respondents earning less than $20,000 versus 24% for the region; 21% of study respondents owned a vehicle while 32% of total system riders had a vehicle in a household. Study riders were younger with 70% below the age of 35 comparing to 49% for the whole region, and there were 10% more male respondents comparing to the whole region (Valley Metro, 2019). Along with surveys, microclimate variables that reflected thermal conditions of respondents were recorded using Kestrel Heat Stress meters. None of the demographic variables were statistically significantly related to thermal sensation vote or thermal comfort.

Table 6
Descriptive statistics of demographic variables (N=83)

Demographic variables		**(N=83) [valid%]**
Gender	Male	66.7
	Female	33.3
Age	18-25	56.8
	26-35	13.6
	36-50	13.6
	51-65	11.4
	65+	4.5
Income	Below 20,000	52.2
	21,000-30,000	19.6
	31,000-40,000	17.4

	41,000-60,000	4.3
	61,000-80,000	2.2
	81,000-100,000	2.2
	100,000+	2.2
Vehicle ownership	Yes	20.9
	No	79.1
Lived in Phoenix for	Less than 3 months	10.8
	3 months to a year	3.1
	1 to 3 years	9.2
	3+	76.9
Part of the daily routine	Yes	60.9
	No	39.1

Survey respondents were asked to choose whether they utilize any of the heat coping strategies while walking to and waiting at the bus stop: “Do you do any of the following when it gets hot? Select all that apply.” and “What do you usually do while you are at a bus stop when it’s hot? Select all that apply” (see Appendix A).

Searching for shade and hydrating or carrying more water were predominant coping strategies while waiting and walking to the stop (Figure 15 and 16).

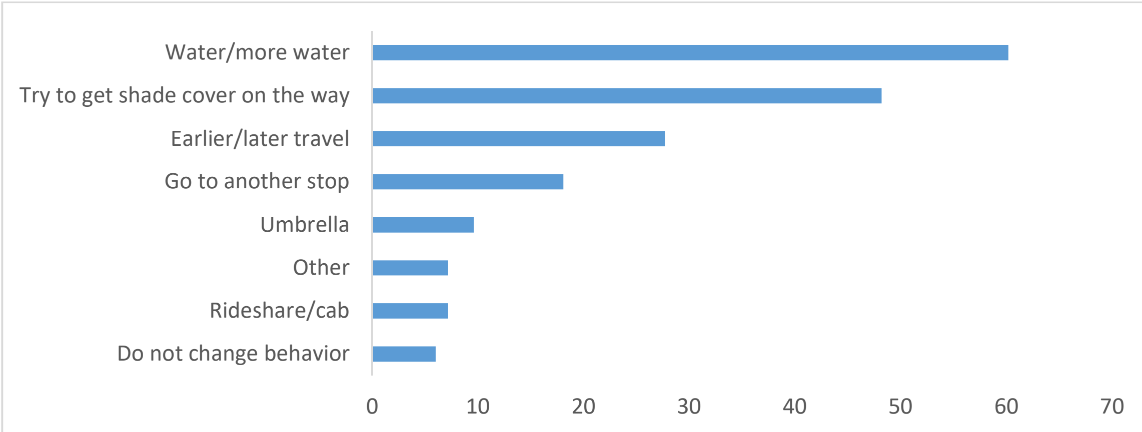


Figure 15
Survey responses to the question: “Do you do any of the following when it gets hot?” Multiple-choice option. Percent selected per each strategy (N=83)

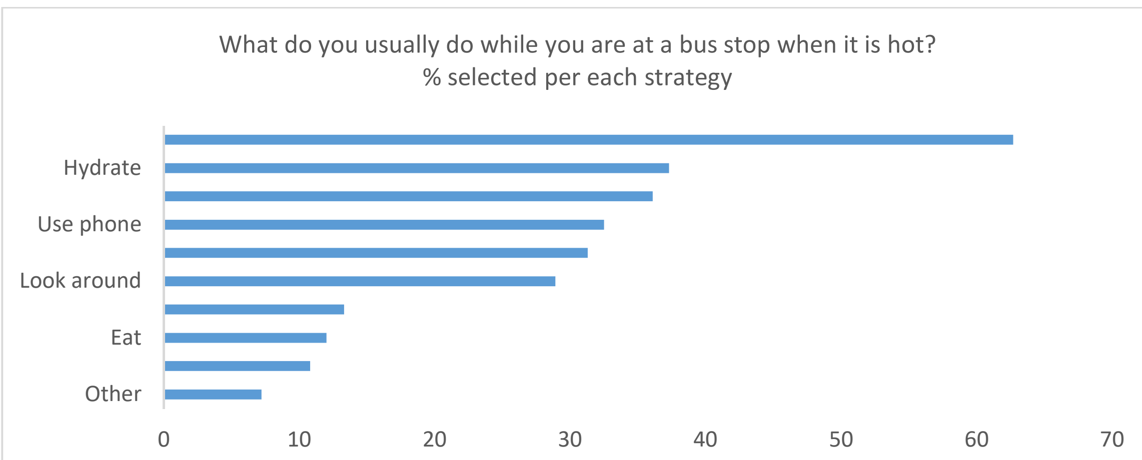


Figure 16
Survey responses to the question: “What do you usually do while you are at a bus stop when it’s hot?“ Multiple-choice option. Percent selected per each strategy (N=83)

Shade structures and trees were the infrastructure features identified most often as having perceived cooling benefits. The question about cooling benefits limited answers to a predefined list of green and grey infrastructure items. However, riders had an opportunity to offer their ideas in the "Other" category. Their suggestions included misters, electric plugs, more built shade and seating, water fountains, and natural shade. The most prevalent complaints about the bus stops were about cleanliness and homeless people occupying the space (Figure 17).

Figure 17
Selected grey and green infrastructure elements perceived to have cooling benefits. Multiple-choice option. Percent selected per each strategy (N=83)

Even though only 3.6% of riders were under a tree when they took the survey (Figure 18), trees were rated nearly as highly as shade structures on cooling benefit. Perhaps riders want more trees at stops; possibly, the effect of perceived control (discussed above) improves thermal comfort even when riders do not stand in tree shade, but can see trees.

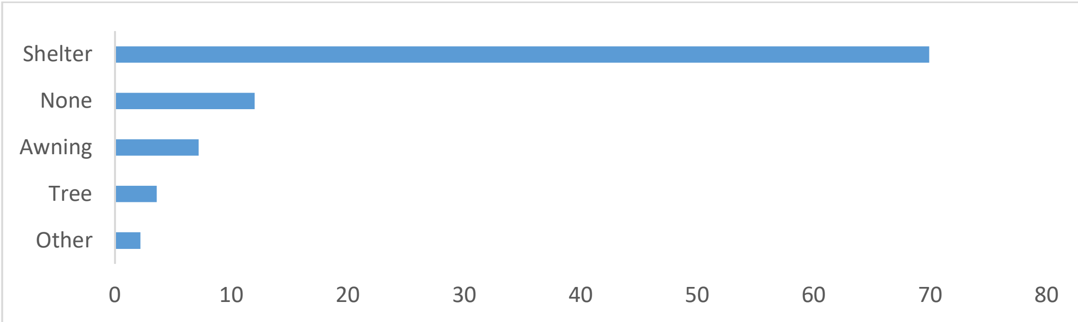


Figure 18
Participants' sun exposure conditions during the survey (N=83)

Table 7
Combined thermal sensation vote for all stop types (N=83)

Very cold	1.2%
Cool	4.9%
Slightly cool	9.9%
Neutral	21.0%
Slightly warm	11.1%
Warm	4.9%
Hot	24.7%
Very hot	22.2%

To examine whether there is a relationship between the stop type and perception of its pleasantness or beauty, we ran a linear regression model. Pleasantness was not significant; however, beauty of the stop was (b=.255, p <.044, R^2=.051). The model slightly improved when standard and advertising stops, looking very similarly, were combined into one category (b=.541, p <.019, R^2=.067).

Nearly a half of study participants felt hot or very hot (Table 7). This explains why air temperature and globe temperature were not statistically significant predictors of thermal sensation vote and thermal comfort.

Thermal comfort was moderately correlated with thermal sensation vote (.505, p<.001). Cross tabulation (Table 8) showed that riders' comfort level is within a wide range of thermal sensation. For example, riders reported feeling comfortable or slightly uncomfortable on a range between 'Very hot' to 'Cool'.

Table 8
Thermal sensation vote vs thermal comfort cross tabulation (N=83)

		Thermal comfort				
		Comfortable	Slightly uncomfortable	Uncomfortable	Very uncomfor table	Total
Thermal sensation vote	Very cold	1				1
	Cool	2	1	1		4
	Slightly cool	6	2			8
	Neutral	12	3	1		16
	Slightly warm	5	3	1		9
	Warm	2	2			4
	Hot	6	6	7	1	20
	Very hot	3	5	5	5	18
	Total	37	22	15	6	80

Both perception of stop pleasantness and beauty were significantly related to thermal sensation vote. We ran linear and ordinal regressions to ensure validity of results. These two methods showed similar outcomes. We found that for one unit of change from unpleasant to pleasant, riders felt cooler by half a point (linear regression: b=-.554, p <.004, R^2=.099; ordinal regression: b=-.557 [-.916, -.199], p <.002).
Perception of stop beauty had a stronger influence on thermal sensation vote than did pleasantness. For one unit of change on the ugly-to-beautiful scale, riders felt cooler by 0.8 point (Figure 19) (linear regression: b=-.800, p <.001, R^2=.168; ordinal regression: b=-.830 [-1.244, -.415], p <.001).

We concluded that perception of stop beauty is a better predictor of thermal sensation vote than stop pleasantness.

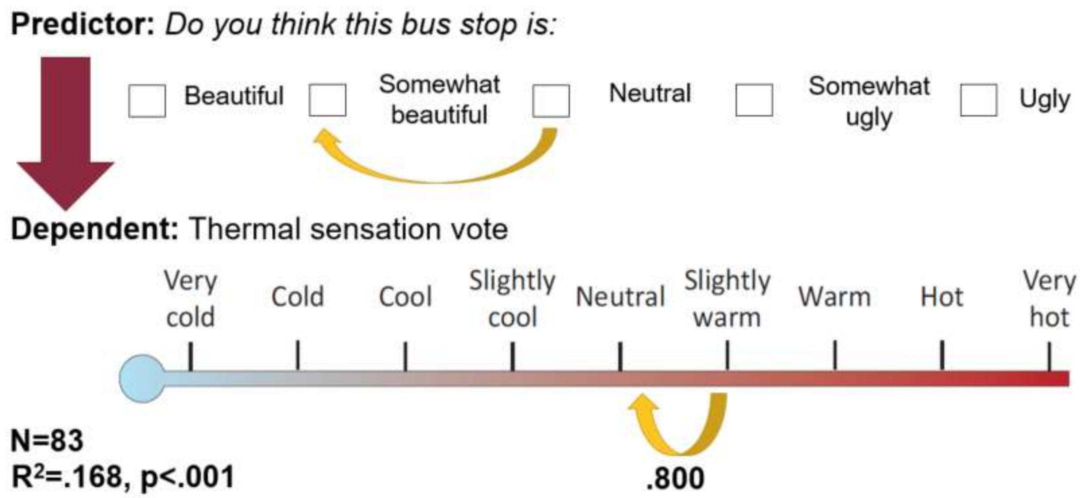


Figure 19
Linear regression analysis of the effect of perception of bus-stop beauty on thermal sensation vote (N=83)

Discussion

Use of public transportation is a necessary and frequently recurring activity that happens outdoors. While optional and social activities are more dependent on favorable outdoor conditions, necessary activities are less so (Gehl, 2011), so they are more likely to cause stress to the human body and mind in extreme climates.

Many American cities that were designed with personal automobile use in mind are now prioritizing sustainability, mixed-use zoning, and non-motorized and public-transit travel. This means that more people are expected to experience the city on their feet; thus, physical conditions and psychological perceptions that affect thermal comfort will become more important. Thermally conscious design in warming climates will help to fulfill sustainable-growth and mobility goals for cities where automobile use has been the dominant form of transportation. It can also alleviate heat stress on the most vulnerable population groups, many of whom have no choice but to rely on public transportation.

The type and characteristics of built infrastructure determine the intensity and duration of individual exposure to heat. Legacy grey-infrastructure systems are predominantly mono-functional (Ahern, 2013); for example, underground water-management systems are designed only to manage urban runoff, transit systems only to satisfy mobility needs, etc. New challenges and uncertainties brought by climate change, rapid urbanization, and the deterioration of existing U.S. infrastructure mean that a new approach to infrastructure is on the horizon (Ahern, 2011; Miller, Chester, & Munoz-Erickson, 2018). Urban-resilience literature suggests that we need to shift towards a safe-to-fail approach and integrate resilience strategies into design and planning (multi-functionality, redundancy, and modularization; social and bio-diversity; multi-scale networks and connectivity; adaptive planning and design) (Ahern, 2011). We argue that built infrastructure that increases individual resiliency to extreme heat needs to integrate cooling functions into its design, to protect users from weather extremes and to extend the temporal range of thermally comfortable conditions. Unfortunately, this is not the case of current bus infrastructure in Phoenix.

The cost of bus-stop shelter in Phoenix is between $6,700 and $16,000. The city makes considerable investments in upgrading existing shade structures and adding new ones to unshaded bus stops (City of Phoenix, 2019). However, both old and new designs follow the same guidelines to choose materials and structure “for strength, durability, ease of maintenance and resistance to weather conditions, graffiti, cutting, fire, and other forms of vandalism" (*RPTA Bus Stop Program and Standards. Findings and Recommendations*, 2008). Even though the guideline for "resistance to weather conditions" calls for design that allows air circulation, avoids retention of hot air, and prevents overheating, perforated metal and special coating are the only recommended materials for bus-stop structures (*RPTA Bus Stop Program and Standards. Findings and Recommendations*, 2008). Metal stops that lack adequate shade with surface temperatures exceeding 40°C are likely to compromise passenger comfort and heat safety at the bus stop. Replacing one metal stop with another metal stop is unlikely to provide a desirable return on investment. We recommend that bus-stop design guidelines prioritize thermal comfort and encourage selection of materials with low emissivity. There is a need to research and test alternative designs and materials that could perform more effectively in the hot cities.

Shelters with landscaping and specialized features cost up to $23,200 (*RPTA Bus Stop Program and Standards. Findings and Recommendations*, 2008). This is a hefty investment for a bus stop that has only 100 boardings a day. If riding the bus were attractive to a greater range of people, public-transit infrastructure investments would become more economically viable. Multifunctional transit stops could offer services that satisfy the needs of not only transit riders, but other people in living or working in the stop area. A bus stop could also become a resting spot, a small-scale cooling and water station, or a service or retail point. Offering a variety of services would improve thermal-comfort conditions, and encourage optional and social activities that are essential for a vibrant city.

Moreover, many cities of the Global South are currently developing their public-transit infrastructure systems and wish to avoid falling into the auto-dependency trap that has characterized development patterns in much of the Global North. It is important to examine current public transit and thermal-comfort conditions in developing cities with climate challenges, to offer alternative development scenarios for sustainable mobility. Bus stops are not the only urban infrastructure that could be improved by routine consideration of thermal comfort in the design phase. Researchers should examine the various kinds of public infrastructure that are intended to facilitate both necessary and optional activities, to identify whether they provides adequate thermal-comfort conditions.

Limitations

This research has several limitations related to the process of data collection and general infrastructure and demographic conditions in the region. Survey sample size reflected low public-transit use in Phoenix (3%), where the car is by far the predominant commuting mode (87%) ("Phoenix, AZ | Data USA," 2016). Since participants were asked to fill out the survey while waiting for the bus, riders who came to the stop less than 5 minutes before the bus arrival did not have time to complete the survey. Thus, demographic questions that were at the end of the survey were often incomplete.

Conclusion

In conclusion, our data suggests that Phoenix bus stops do not provide thermally comfortable conditions for riders in summer. The mean ambient temperature for all bus stops was 39°C and globe temperature was above 45°C.

Analysis of micrometeorological variables at stops showed that trees were most effective in reducing ambient temperature by more than 1°C on average and the bus-stop shelter was the least effective. Sade form the advertising sign was most effective in reducing globe temperature, reinforcing the importance of vertical shade for thermal comfort. While trees and bus-stop shade performed similarly for reducing globe temperature, vegetated awning was least effective due to the poor maintenance and scarcity of vegetated vines. Analysis of surface temperatures of prevailing material types showed that all studied sun exposed man-made materials included temperatures above the skin burn threshold. However, shade was effective in lowering the temperature by as much as 20°C.

Recorded high temperatures were in alignment with respondents' perceptions. Almost half of the riders reported feeling hot or very hot, and more than a half experienced some degree of thermal discomfort. Access to shade and drinking water was selected as preferred heat coping strategy. Results indicate importance of psychological aspects, for instance people selected trees as important cooling elements but did not use their direct shade; and beauty was a significant predictor of thermal sensation.

Overall, strategic placement of green and grey infrastructure elements and careful consideration of material properties for thermal comfort can help to mitigate heat exposure and improve thermal sensations of public infrastructure users. Thus, thermally conscious design needs to be a priority in cities challenged by climate extremes.

CHAPTER 3

PERCEPTION OF THERMAL COMFORT IN RELATION TO STREET INFRASTRUCTURE

Abstract

Designing cities for thermal comfort should be a priority in the warming and urbanizing world. As cities continue to break extreme heat records, it is necessary to develop and test new approaches capable of tracking thermal sensations influenced by both microclimate conditions and subjective reactions of the individuals. The influence of built infrastructure on walking pedestrians is not well explored, but combining sensing technologies with simultaneous collection of user experiences is a promising research direction to shorten the gap.

We examined the relationships between the built environment, heat perception, and behavioral coping mechanisms in one of the most heat vulnerable Phoenix neighborhoods. Using Phoenix as an example, where extremely hot summer temperatures are becoming a norm, can help to address heat challenges of other cities that are facing rising temperatures.

This study is an experimental citizen science project in which participants were interviewed during a 1-hour walk around the neighborhood, and recorded their experience in a field guide. Walkers wore GPS devices and microclimate measurements were taken to gain deeper insights on subjective heat perception and physical body heat accumulation during the walk. Results revealed the differences in heat perception across a variety of urban landscapes. Participants identified preferred and most challenging

locations, and gave ideas on what could improve their experience. Combined GPS and microclimate data mapped in GIS visualized dependencies between the streetscape, microclimate and thermal perceptions.

This project is one of the first to examine the impact of urban environment on dynamic psychological and physiological responses to heat. Using sensing technologies and qualitative research instruments, this research will inform the design changes in the neighborhood that will undergo redevelopment. It can serve as an example for other cities striving to adapt urban microclimates to new extremes.

Introduction

Cities around the world keep breaking heat records every year, compromising wellbeing of urban residents (WMO - World Meteorological Organization, 2019). This fact raises the need to explore how current urban design practices affect pedestrian thermal comfort to improve walkability and livability in the warming world. To get a deeper understanding of pedestrian experiences, we combined sensing technologies with real-time qualitative research tools. Using walking interviews, we will tell the story of seven street segments in one of the hottest Phoenix neighborhoods that is currently slated for redesign.

To understand how humans interact with environment, it is essential to take into account both objective and subjective evaluations, the “city on the ground and the city in the mind”(Pacione, 2003). Pacione has developed a stress model of environmental impact, which contains both objective environmental conditions and individual characteristics of the person. Four types of environmental stressors are cataclysmic events, ambient stressors, stressful life events, and daily hassles. When perceived conditions are outside of the optimal range of the person, it causes stress and activates coping. Successful coping results in adaptation but can be accompanied by the after effects, such as fatigue and reduced ability to cope with the next stressor. Unsuccessful coping can cause exhaustion, reduced performance and possible illness and mental disorders (Pacione, 2003).

The outdoor built environment can negatively influence urban livability by both affecting environmental variables that can potentially become environmental stressors, and also by failing to satisfy subjective human needs such as need for contact with nature, aesthetic satisfaction, need for recreation, play, and social interactions (Matsuoka & Kaplan, 2008).

Performing daily outdoor activities in hot and arid climates can result in exposure to severe heat and compromised thermal comfort. Below, we have adapted the stress model of urban impact (Kuras et al., 2017; Pacione, 2003) to the stress of heat exposure (Figure 20).

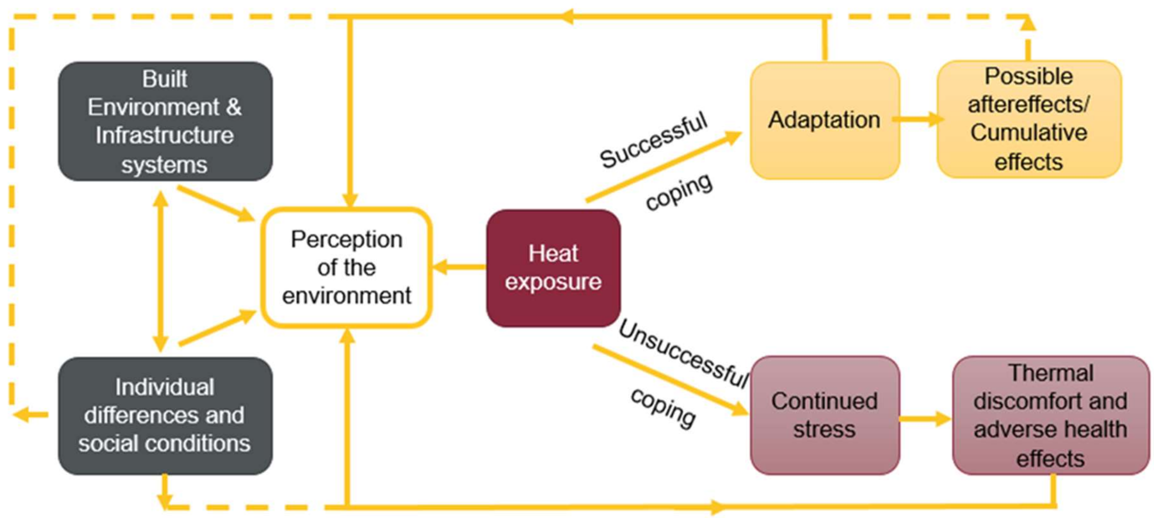


Figure 20
A model of urban impact under the stress of heat exposure. Adapted from Pacione (2003) and Kuras et al. (2017)

From physiological perspective, thermal comfort depends on the energy balance between the body and the environment. Environmental variables that affect thermal comfort are ambient temperature, radiant temperature, humidity, and air movement; behavioral variables include metabolic rate and clothing (Fanger, 1972). Metabolism, skin temperature, blood flow, and sweat production are the main physiological processes that are responsible for thermal comfort in the body. These processes depend on the activity level (Vanos, Warland, Gillespie, & Kenny, 2010). Thus, walking or exercising individuals will experience thermal comfort in a different way than people who do not move. Psychological perception is also changing at higher metabolic rates (Vanos et al., 2010).

Thermal comfort and urban design literature identified qualities of the outdoor environment that affect perceptions of comfort and walking behavior of individuals

(Ewing & Handy, 2009; Nikolopoulou & Steemers, 2003). Nature, expectations about climate in relation to previous experience, time of exposure, and ability to choose microclimate conditions affect thermal perceptions (Nikolopoulou & Steemers, 2003). Ewing and Handy (2009) developed a framework of walking behavior (Figure 21) that is affected by physical features, urban design qualities and individual reactions. Even though framework includes weather as a factor of the physical features, there is little evidence on how exposure to weather extremes, such as extreme heat, affects walking behavior, and how differences in street infrastructure affect perceptions of thermal comfort.

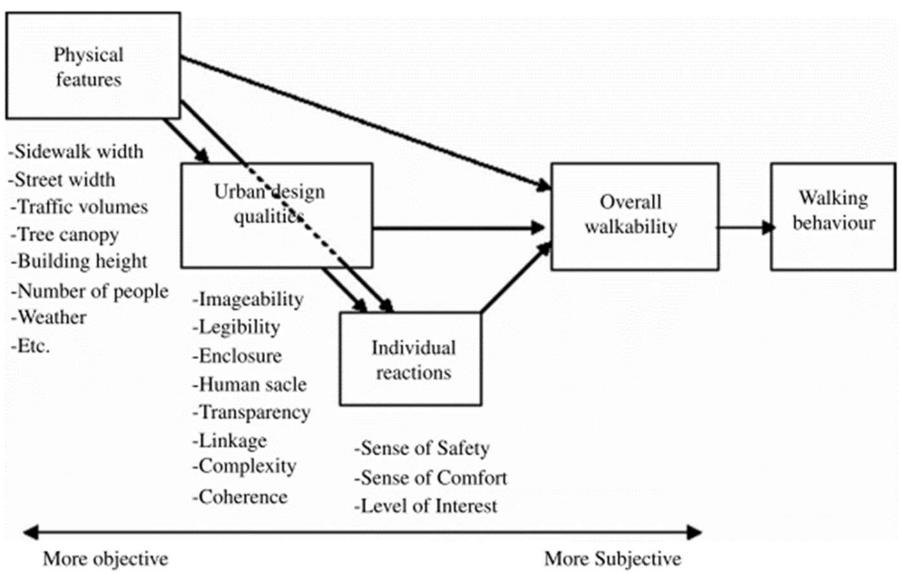


Figure 21
Conceptual framework of walking behavior (Ewing & Handy, 2009)

A promising method to study the effect of place and climate on health and wellbeing of walking individuals is the walking interview. Walking interviews or "Go-

Along" interviews is the method that recently gained popularity among social scientists interested in exploring in-depth relationships between the interviewees and a place (Carpiano, 2009; Evans & Jones, 2011; Riley & Holton, 2017). The benefit of the walking interview is that participants are exposed to multisensory experience and, thus, enable the researcher to explore their attitudes about surrounding environment. Walking interviews can provide information on insights and feelings that are not easily articulated or commonly verbalized (Evans & Jones, 2011; Riley & Holton, 2017).

The objective of this study is to test how the framework of walking behavior (Ewing & Handy, 2009) applies to urban environments under the stressor of extreme heat; and to explore how various types of green and grey infrastructure affect thermal perceptions of pedestrians. To achieve that, we combined data from walking interviews, microclimate-sensing techniques, health measurement devices and survey instruments. The Heat Mappers event on a hot day in a Phoenix neighborhood was utilized as a case study.

Methods

We interviewed twelve participants during the walk. Relationships between street infrastructure, microclimate conditions and thermal perceptions were explored using deductive coding, calculating physiological equivalent temperature and spatially mapping the results.

Study site

Edison Eastlake has the highest concentration of public housing in Phoenix, with 67% of residents living in poverty. Community is characterized by degraded infrastructure, lack of amenities and poor environmental quality due to proximity to a freeway and a superfund site. Edison Park is home to homeless population, gangs and drug exchanges (*Edison Eastlake Community Health Impact Assessement*, 2017). This predominantly Latino neighborhood was shaped by the history of racial segregation and environmental injustice (Bolin, Grineski, & Collins, 2005).

In an effort to break the poverty trap and improve neighborhood conditions, Edison Eastlake was awarded Choice Neighborhoods Planning and Action Grant through U.S. Department of Housing and Urban Development (HUD). Redevelopment aims to improve public safety, ensure street walkability and provide public spaces with amenities and educational opportunities. Old public housing will be replaced with mixed-income units. Plan also includes improving thermal comfort in the neighborhood, since it is currently one of the hottest and most vulnerable to heat Phoenix neighborhoods. These improvements will include changes in layout and green and grey infrastructure application (*Edison-Eastlake One Vision Plan*, 2018).

Edison Eastlake neighborhood is an exceptional opportunity to track the effect of redevelopment efforts by implementing pre and post data collecting campaigns. Heat Mappers walk was one of such efforts to establish a baseline of thermal comfort of the current neighborhood conditions. It is an experimental citizen science project with participants helping to create a neighborhood ‘heat map’. Participants, equipped with

GPS devices, engaged in a 1-hour walk around the neighborhood, recorded their experience in the field guide and were interviewed along the route. The Heat Mappers walk was organized by The Nature Conservancy in Arizona in partnership with Museum of Walking, Phoenix Revitalization Corporation, and Arizona State University's Urban Climate Research Center and Knowledge Exchange for Resilience. The Heat Mappers event happened on Saturday, September 29, 2018, 4:00pm-6:00pm. The average temperature for this during time was 38 °C. Twenty-two walkers, recruited through various information channels, walked the route and filled out the field guide. Out of the total twenty-two, fourteen participants wore GPS devices and were interviewed along the route. This paper will analyze the data from the above-mentioned fourteen participants who participated in the interviews.

Data collection

Participants received a field guide that included the route map (Figure 22) and survey questions in relation to each walk segment (Appendix B). A 3-mile walk started in Edison Park and included three residential street segments with various infrastructure characteristics, minor arterial road, large area of vacant land, two hospital parking lots, and a school playground. Neighborhood land use map is shown in Figure 23 (Maricopa Association of Governments, 2017). Seven stops divided the route into street segments. Detailed description of street segments is presented in Table 9. For the analysis, segments 5 and 6 were divided into two due to the differences in land use and infrastructure properties. Images of the segment are presented in Figure 24. Images of bus stops along the minor arterial street are shown in Figure 25.

Field guide survey questions (Appendix B) consisted of three parts. The first part included basic demographic information (age and gender), duration of average summer outdoor exposure and perceived health risks in relation to normal and extreme summer heat. In the second part walkers were asked about the clothing conditions during the walk and initial thermal sensation vote and thermal comfort. Third part included stop specific questions, perception of the walked street segment, proposed changes, and estimated percent of shade on the route, thermal sensation and thermal comfort level. Water was available at every stop and participants were given a sticker as an incentive for reaching the station.

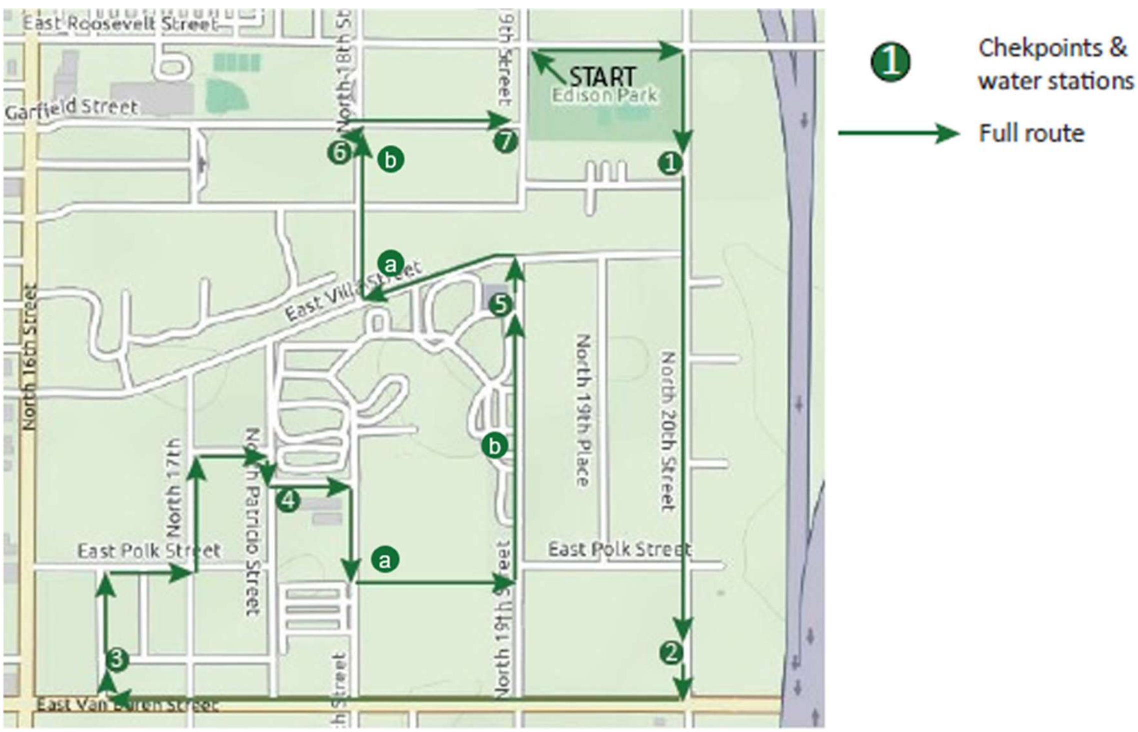


Figure 22
Heat Mappers Walk route map. Edison Eastlake Neighborhood

Figure 23
Existing land use map (Maricopa Association of Governments, 2017)

An interviewer accompanied each participant along the whole walk. Two out of ten interviewers interviewed two people at the same time. Interviewers had prior onsite training.

Interviews started with open-ended questions about walking preferences and behavioral changes during the hot part of the year. Similar street specific questions were asked throughout the walk: “What do think about this street? What do you like or dislike about it? How thermally comfortable do you feel and how pleasant? What would you change about the street?” Furthermore, interviewers probed for street specific features, such as traffic, vegetation, opinions about bus stops etc. Final questions at the end of the route asked opinions about relationships between walking, wellbeing and outdoor environment. Interviews were recorded and transcribed.

To get individual level data on sun exposure and exertion, every walker wore a GPS device. Micrometeorological data was collected using biometeorological cart (MaRTy) (Middel & Krayenhoff, 2019). MaRty collected environmental data that influence thermal sensations at a scale at which people experience. The data was used to calculate physiological equivalent temperature (PET) for each study participant. PET is defined as the air temperature at which the human body is usually at heat balance indoors and compared to outside conditions and is commonly used in thermal comfort studies (Crewe, Brazel, & Middel, 2016). This project was approved by the Institutional Review Board of Arizona State University (STUDY00008752).

Table 9

Description of infrastructure by street segment. Heat Mapper walk event

Segment name	**1. Edison Park**	**2. Single story residential**	**3. Commercial**	**4. Vacant land**	**5 (a). Hospital parking**	**5(b). Single story residential**	**6(a). Two stories residential**	**6(b). School playground**	**7. End of the walk. Vacant land**
Street	E Roosevelt/ N20th St.	20^{th} St.	Van Buren	N 16^{th} Pl/ E Polk St./N 17^{th} St./E Taylor St.	E Taylor St./Hospital walkway/N 18^{th} St.	N 19^{th} St.	E Villa St/N 18^{th} St.	E Garfield St.	E. Garfield St.
Street type	Local	Local	Minor Arterial	Local	Local	Local	Local	Local	Local
Segment description	Public park	Public housing on the west side and mix of residential, commercial, religious and vacant land on the east	Low commercial, hospital, residential and vacant land	Large area of vacant land	Two hospital parking lots	Hospital on the west and public housing on the east	Public housing on E Villa and east of 18^{th} St, mixed-income housing on the west	Edison Elementary School playground	Vacant land on the north, government building and parking on the south
Description of structures and buildings	Small playground and sitting area with shade structures.	Single story buildings with street setbacks.	Sparse single story buildings with adjacent parking lots in front or on the side of.	Mostly empty land with utility poles and two buildings in the middle of the lots.	Large open area with several multi-story hospital buildings.	Single story buildings with street setbacks on the east and hospital buildings on the west	Two-story buildings with street setbacks. Gated community on the west	Playground with metal and plastic equipment. Several playing fields	Predominantly single-story with one two-story building
Ground cover	Concrete walkways, grass coverage	Asphalt road and concrete sidewalks.	Asphalt road and concrete sidewalks.	Asphalt road and concrete sidewalks. Large patches of dirt.	Asphalt parking lots and concrete sidewalks.	Asphalt road and concrete sidewalks.	Asphalt road and concrete sidewalks.	Sand play area with concrete walkways	Asphalt road and concrete sidewalks. Dirt vacant land.

Number of lanes	One lane in each direction with bike lanes on both sides	One lane in each direction with bike lanes on both sides	Two lanes in each direction separated by a continuous left-turn lane	One lane in each direction	One lane in each direction	One lane in each direction	One lane in each direction	One lane in each direction	One lane in each direction
Description of vegetation	Grass coverage throughout the park. Scattered large trees with dense canopies and palm trees.	Large crown trees and grass lawns on the west side. Sparse trees and bushes on the west	Mostly palm trees. Dirt sidewalk buffer with small bushes at several locations	Sparse palm trees on the perimeter	Trees and bushes on the perimeter of one of the parking lots	Trees and grass on both street sides	Desert trees and xeriscaping on the west and grass lawns with small shrubs in the east	Small patch of grass and three trees on the northern corner	Small shrubbery

1. Edison Park **2. Single story residential**

3. Commercial

4. Vacant land

5(a). Hospital parking **5(b). Single story residential**

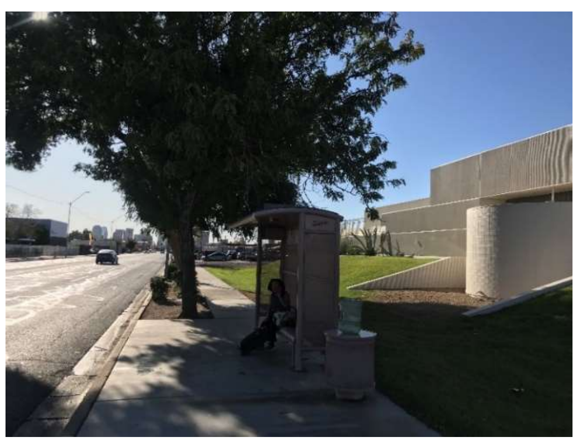
6(a). Two stories residential **6(b). School playground**

7. End of the walk. Vacant land

Figure 24
Images of street segments at the Heat Mappers Walk. Edison Eastlake Neighborhood

Bus stop 1

Bus stop 2



Bus stop 3

Figure 25
Images of bus stops along segment 3.Commercial (Van Buren Street). Edison Eastlake Neighborhood

Data analysis

Demographic and Likert scale questions from the surveys were analyzed using descriptive statistics. Statistical significance tests were not performed due to small sample size.

PET index was calculated in the Rayman model (Matzarakis & Rutz, 2010) for each participant. Collected subject data was spatially joined with the MaRTy data; each participant location point was assigned the closest value from MaRTy. A RayMan input file was created, assuming clothing of 0.5 and metabolic rate of 110 W (Middel & Krayenhoff, 2019). Data was spatially mapped using geographic information systems.

Interview data was analyzed using qualitative data analysis software MAXQDA 2018. Themes were identified using structural codes, themes derived from urban design and thermal comfort literature and repetitions (Bernard, 2006; Ryan & Bernard, 2003). All interviews were manually coded by street segments as they appeared in the transcripts.

Results

Eight females and six males participated in the walking interviews. The majority were between 25 and 44 years old (Table 10). Participants took individual precautions for long-term sun and heat exposure. Twelve wore a hat, eleven wore sunglasses, nine used sunscreen, and eleven brought a water bottle.

Table 10

Interview participants’ age distribution (N=14). Heat Mapper Walk. Edison Eastlake Neighborhood

Age	Frequency	Percent
18-24	1	7%
25-44	8	57%
45-64	3	21%
65+	2	15%

Graphic representation shows that there are wide variations of thermal sensations and thermal comfort votes between individual participants (Table 11 and Table 12). This is in agreement with the results on thermal comfort of bus riders in another Phoenix neighborhood (Chapter 2). Segments 5 and 6 that included one and two story residential developments with landscaping and big trees were rated as most pleasant, and segments 3 and 4 with main arterial street and vacant land were perceived as least (Table 13).

Table 11

Thermal sensation vote vs street segment cross-tabulation (N=14). Heat Mapper walk event. Edison Eastlake Neighborhood

Gender	Age	Start of the walk	1. Edison Park	2. Single story residential	3. Commercial	4. Vacant land	5. Hospital parking/ Single story residential	6. Two stories residential/ School playground	7. End of the walk. Vacant land	Average per user
Female	25-44	3	2	3	4	4	4	3	3	3.3
Female	25-44	2	3	3	4	3	3	2	3	2.9
Female	25-44	3	4	4	3	4	3	4	4	3.6
Female	25-44	2	3	3	3	3	3	3	2	2.8
Female	45-64	1	2	0	2	0	0	0	1	0.8
Female	45-64	2	2	2	3	3	3	3	3	2.6
Female	65+	1	1	1	2	2	1	3	2	1.6
Female	65+	3	3	3	3	3	3	3	3	3.0
Male	18-24	1	1	0	1	1	1	0	-1	0.5
Male	25-44	3	0	1	1	0	-1	-1	-1	0.3
Male	25-44			0	0	0	0	0		0.0
Male	25-44	1	1	2	3	2	2	2	1	1.8
Male	25-44	3	2	3	2	1	2	0	-1	1.5
Male	45-64	1	1	2	3	2	2	1	1	1.6
Average per segment		**2.0**	**1.9**	**1.9**	**2.4**	**2.0**	**1.9**	**1.6**	**1.5**	

Legend:

Slightly cool	Neutral	Slightly warm	Warm	Hot	Very hot	Not data
-1	0	1	2	3	4	

Table 12

Thermal comfort vote vs street segment cross-tabulation (N=14). Heat Mapper walk event. Edison Eastlake Neighborhood

Gender	Age	Start of the walk	1. Edison Park	2. Single story residential	3. Commercial	4. Vacant land	5. Hospital parking/Single story residential	6. Two stories residential/ School playground	7. End of the walk. Vacant land	Average per user
Female	25-44	3	2	3	3	4	4	3	4	**3.3**
Female	25-44	1	2	2	3	2	3	2	3	**2.3**
Female	25-44	2	3	3	3	3	3	3	3	**2.9**
Female	25-44	2	2	2	3	3	3	3	2	**2.5**
Female	45-64	1	2	1	2	1	1	1	2	**1.4**
Female	45-64	2	2	2	2	3	3	3	3	**2.5**
Female	65+	2	2	2	2	2	2	3	3	**2.3**
Female	65+	2	2	3	3	3	3	3	3	**2.8**
Male	18-24	2	1	1	2	2	2	1	1	**1.5**
Male	25-44	2	1	1	1	1	1	1	1	**1.1**
Male	25-44	2	2	2	2	2	2	2		**2.0**
Male	25-44	2	2	2	3	3	2	3	1	**2.3**
Male	25-44	2	2	3	1	1	2	1	1	**1.6**
Male	45-64	2	2	2	3	2	2	2	2	**2.1**
Average per segment		**1.9**	**1.9**	**2.1**	**2.4**	**2.3**	**2.4**	**2.2**	**2.2**	

Legend:

Comfortable	Slightly uncomfortable	Uncomfortable	Very uncomfortable	Not data
1	2	3	4	

Table 13

Pleasantness vote vs street segment cross-tabulation (N=14). Heat Mapper walk event. Edison Eastlake Neighborhood

Gender	Age	1. Edison Park	2. Single story residential	3. Commercial	4. Vacant land	5. Hospital parking/Single story residential	6. Two stories residential/ School playground	7. End of the walk. Vacant land	Average per user
Female	25-44	-1	-2	-2	-2	-1	-1	-1	**-1.4**
Female	25-44	-1	-1	-2	-1	1	1	-1	**-0.6**
Female	25-44	0	1	-1	-1	2	2	1	**0.6**
Female	25-44	-1	-2	-2	-2	-1	-2	-2	**-1.7**
Female	45-64	0	0	-1	0	1	1	-1	**0.0**
Female	45-64	-1	0	-1	-2	2	1	-2	**-0.4**
Female	65+	-1	-2	-2	-2	1	-1	-1	**-1.1**
Female	65+	-1	-1	-1	-2	1	0	-1	**-0.7**
Male	18-24	0	1	-1	-1	0	0	0	**-0.1**
Male	25-44	0	0	0	-1	2	2	0	**0.4**
Male	25-44	2	0	0	-1	1	0		**0.3**
Male	25-44	0	-1	-1	1	1	-1	-1	**-0.3**
Male	25-44	0		0	2	2	2	0	**1.0**
Male	45-64	-1	-1	-2	-1	1	-2	-1	**-1.0**
Average per segment		**-0.4**	**-0.6**	**-1.1**	**-0.9**	**0.9**	**0.1**	**-0.8**	

Legend:

Unpleasant	Slightly unpleasant	Neither pleasant or unpleasant	Slightly pleasant	Pleasant	Not data
-2	-1	0	1	2	

The street segment with the highest mean PET temperature 49.2°C was the vacant land (segment 4) on the west side of the neighborhood, followed by the arterial road (segment 3) (Figure 26). The lowest was the segment with two-story residential development (segment 6) with the mean PET 44.3°C, followed by the last segment leading back to the park (segment 7), which is likely attributed to the afternoon cooling effect. Segment 5 with one-story residential development that was selected as the most pleasant segment had the mean PET 45.7°C. Boxplot representation of PET values per street segment (Figure 27) showed a wide distribution of minimums and outliers reflecting the diversity in microclimate due to differences in street infrastructure.

Mean PET, thermal sensation, thermal comfort and pleasantness vote per street segment (Figure 28) revealed complex interactions between physiological and psychological aspects of thermal comfort. For instance, streets with the highest PET were also perceived as the hottest, less thermally comfortable and less pleasant. However, streets with lower PET varied in their thermal comfort and aesthetical perceptions. The psychological effect of time of exposure became visible, as the average thermal comfort vote increased towards the middle of the walk, even when PET lowered, for example, segments 2 and 5 had the same PET, but segment 5 was perceived as less comfortable.

Figure 26
Spatial distribution of PET index for study participants (N=5163). Heat Mapper walk event. Edison Eastlake Neighborhood

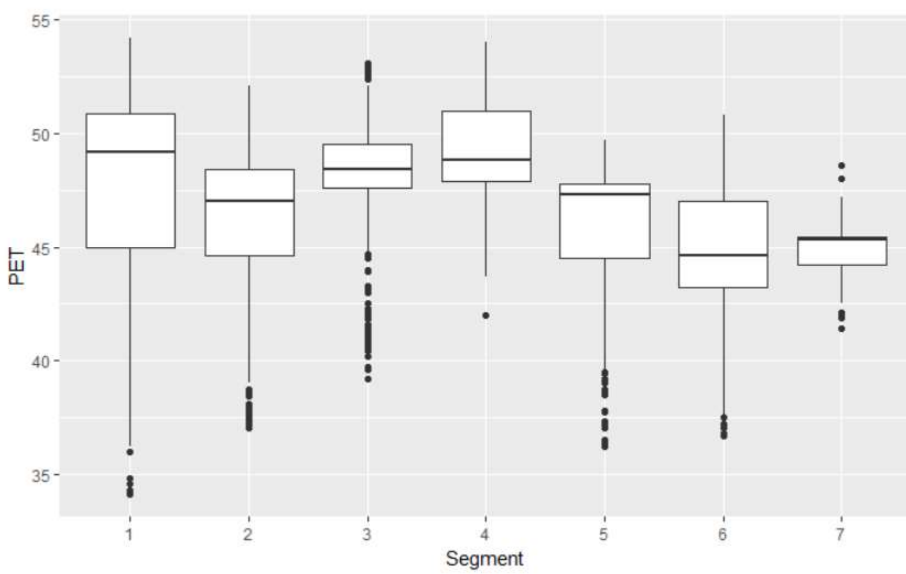
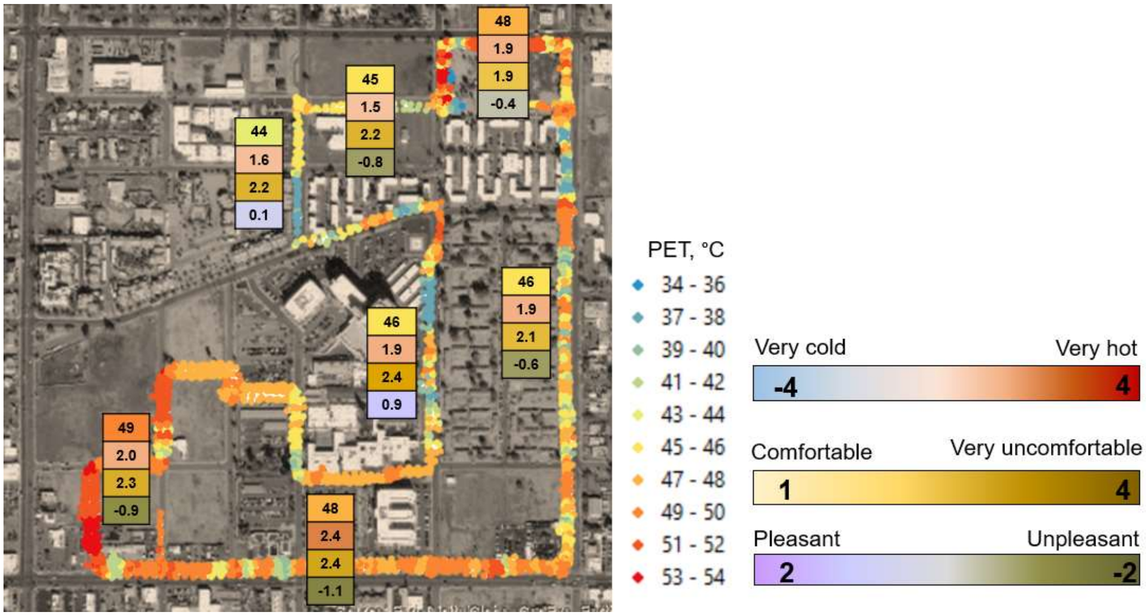


Figure 27
Boxplot of the PET by the street segment (N=5163). Heat Mapper walk event. Edison Eastlake Neighborhood



From top to bottom: PET (N=5163); Thermal sensation vote (N=14), 9-point scale; thermal comfort scale (N=14), 4-point scale; perception of pleasantness (N=14), 5-point scale. Heat Mapper walk event. Edison Eastlake Neighborhood

Figure 28
Average PET and thermal/aesthetical perceptions per street segment. Heat Mapper walk event. Edison Eastlake Neighborhood

Applying the framework of walking behavior

Interviews were coded according to the framework of walking behavior developed by Ewing and Hardy (2009) and divided into positively and negatively perceived by the participants, as well as suggested changes to improve perceptions (Table 14). Participants revealed a wide range of themes that were present in the framework, such as details of what they liked or disliked about infrastructure elements, landscaping, sounds, smells, textures etc. However, unlike Ewing and Hardy’s framework, where weather was included as part of the physical features without an evident effect, in this research, heat was a major stressor affecting themes itself as well as perceptions about environment and walkability. That is why shade, or lack thereof, was often mentioned as a positive or negative factor in street perception.

Below we present main themes extracted from the interviews with supporting quotes that demonstrate participants' perceptions and thermal sensations towards selected green and grey infrastructure elements, urban design qualities, and their individual reactions in respect to comfort and heat.

<u>Physical features. Green infrastructure</u>

Green infrastructure elements had the most positive effect on participants' perceptions. Prevalent themes in relation to particular types or green infrastructure are discussed below.

"These trees makes all the difference in the world!"

Shading and cooling: Trees were identified as having major impact, above other cooling strategies, on influencing thermal comfort. Participants identified that trees need to be functional, provide shade, and, thus, use of specific kinds and strategic placement is important for both outdoor comfort and lower electricity bills for the buildings: "The shade of the trees make such a big difference. Yeah, I feel a lot more comfortable." *Attractive and pleasant:* Streets with large trees were perceived as most pleasant. Tress were mentioned as important elements to provide rest and gathering places for people. Planting trees was the most popular improvement strategy: "Definitely, trees are important. Aesthetically and being able to sit under the shade tree. During the summertime is when you could appreciate it."

Buffer: Another important benefit from trees was noise reduction from nearby freeway and as a barrier between the sidewalk and the road.

Value: Trees were perceived as valuable infrastructure elements. Interviewees acknowledged that trees are a long time investment and preserving big and mature trees should be prioritized during the redevelopment: "Well you can't do that now because you'd have to end up pulling up these trees which you wouldn't be willing to do."

"...palm trees, which are the most useless trees in the universe"

No shade: Majority agreed that palm trees do not provide adequate shade in comparison to other trees: "Palm trees aren't great shade in that order. They don't make that same kind of shade as that one tree that has someone camped out under it"

Out of place: Several participants expressed concerns about non-native nature of the trees as well as random placement: "Yeah, they're kind of like the one thing that's out of place here, even though there are so many. Someone must've just thought oh let's put a bunch of palm trees here. Do they function as wind breakers? They're just plotting them in the ground."

Carbon storage: Several interviewees brought up a positive aspect of carbon storage: "It's just this brown place covered in palm trees. The thing about palm trees is that they store carbon, so you want to leave them here".

Grass and xeriscape

Majority positively reacted to the grass, acknowledging perceived cooling. However, participants also felt conflicted about it, since grass requires intense irrigation, and water is a scarce resource in a desert environment. Several heat walkers mentioned that they converted their yards to xeriscape. Participants were willing to compromise grass in favor to desert landscaping: "Well, they don't have any plantings in this area. They could put xeriscape; it could be very lush with less use of water, bringing down heat."

Physical features. Grey infrastructure

"Tree shade is better than building shade, but in the absence of tree shade, I'll take building shade."

Physical features of built infrastructure were positively perceived when they provided shade, offered protection from traffic, or encouraged public life. Negative opinions mostly referred to the lack of infrastructure. Participants characterized infrastructure materials in terms of their thermal properties. Vocabulary of thermal meanings for materials mentioned during the interview is presented in Table 15. Overall, interviewees perceived natural materials cooler than manmade.

Chain link fences were attributed to reducing comfort, safety and having poor visual appeal: "Well, we are on the shade of this fence, but there is barbed wire. I don't get a comforting feel from that." "Over here, I'm getting blasted by the heat, there's this barbed wire." "[…] the barbed wire and fences. You feel like you're walking through a warzone."

Urban design qualities

Ewing and Hardy identifies five urban design qualities affecting walking behavior: imageability, enclosure, human scale, transparency, and complexity. Imageability is a quality that makes a place recognizable, and is formed by particular arrangements of physical features or their unique characteristics. Enclosure is identified by the presence of vertical elements on the street, such as buildings, trees, streetlights, etc. Human scale is related to a proportion of physical features to the size of the human. Windows, doors and other elements that allow visible human activity seen beyond the street enhance transparency. Complexity characterizes visual richness of the street and can be enhanced by various physical features, such as buildings, trees, landscaping, street furniture, etc. (Ewing & Handy, 2009).

Even though urban design qualities are more abstract and could be difficult to articulate by non-professional audience, interview participants alluded to several urban design features. They talked about absence of visual attractiveness at some areas, positive impact of seeing people performing outdoor activities, importance of public art and street furniture, and impact of colors: ”I like something at the end that feels like a reward, either a beautiful view or if I were here and walking, I would like to see a bench right there. You could sit on the benches, and look at the mountains or the sunrise or the sunset, things like that would encourage me to walk in an area.”

Table 14
Testing applicability of framework of walking behavior developed by Ewing and Handy (Ewing & Handy, 2009)

Street segment	**Positive**		**Negative**		**Improvements**	
1. Edison Park	PF PF/UD PF	Splash pad Children playing Grass and trees	PF PF/UD PF PF	Lack of shade Busy road nearby Lack of trees Lack of playing structures for children	PF PF UD PF/UD PF	Add gathering places in the shade Create a community garden Add public art Add benches from alternative to metal materials Add speed bumps to the road
2. Single story residential	PF PF PF PF/UD PF/UD PF	Big trees Shade from buildings and trees Grass Courtyards Children playing Bike lane	PF/UD PF PF/UD PF/IR PF PF PF/UD	Noise from the freeway Litter on the vacant lot Fence on the east side Lack of street lights Parked cars Narrow sidewalk Lack of public life	PF PF PF PF PF/UD PF/UD PF	Plant trees Widen sidewalks Add benches Clean up and infill vacant lots Add public art Add public amenities Add xeriscape landscaping
3. Commercial			PF PF PF/UD IR PF/UD UD	Lack of trees and vegetation Absence of shade Noise from cars Feeling vulnerable Many vacant lots No visual appeal	PF PF PF PF PF	Fill in vacant lots with businesses and housing Widen sidewalk Add public amenities Provide shade Create alternative pedestrian route with less traffic

			PF/UD PF	Sun in the face Heat from concrete and asphalt		
Bus stop 1			PF PF/IR PF PF UD	Sun exposed metal bench too hot to sit on Shade behind the structure not sufficient Design does not provide shade in the hottest hours Barbed wire fence behind Unattractive color	PF PF PF PF/UD	Add side panels Use alternative 'cooler' material Implements shade conscious design Add useful information (bus schedule, hotline)
Bus stop 2	PF PF PF	Pullout reduces vulnerability feeling Nearby bushes look appealing and cool the ground More green	PF PF	Sun exposed metal bench Space inside the shelter too hot		
Bus stop 3	PF PF IR PF	Big trees and grass Plenty of shade Feeling calmer Maintained landscaping behind the stop			PF	Use alternative 'cooler' material

4. Vacant land	PF UD PF PF PF PF	No traffic noise View of the mountains Better street for biking Sun is not in the face Dirt feels cooler Breeze	UD IR PF PF IR IR	Visually bland Feeling unsafe Cracked sidewalk Hot asphalt Feels abandoned Feeling unwelcomed	PF PF PF UD	Create a village center with amenities Provide shade Add landscaping along the road Create visual landmarks
5 (a). Hospital parking	PF PF	Sun in the back Tress on the parking lot	PF PF PF IR	Insufficient shade for cars Walkways to buildings are not shaded Too much asphalt Uncomfortable to walk on hospital property	PF PF PF PF PF	Add solar shade to parking lots Use alternative 'cooler' pavement Plant more trees Add curb cuts for irrigation Provide rest places
5(b). Single story residential	PF PF/IR PF PF/IR PF/IR	Shade from buildings and trees Life on the street Grass Birds chirping Blossom smell	PF/UD PF	Potential noise form helicopter pad Parked cars on the street	PF PF PF PF/UD PF PF/UD PF	Create designated parking space Widen sidewalk Narrow the road Add plant barrier between Add bike lane Add benches Install shade structures in the residential courtyards
6(a). Two stories residential	PF PF	Xeriscape landscaping Breeze	PF IR	The wall of the gated residential housing Gated housing feels impersonal	PF UD	Create shade continuity Add public art

			PF PF PF PF	Wasteful grass on the side of public housing Shade is not continuous Bad smell Too much asphalt		
6(b). School playground	PF PF UD PF	Variety of playing fields Good state of equipment Bright colors Patch of grass	PF PF PF/IR PF PF PF	Shade structure is too high to provide shade Metal and plastic equipment too hot to touch Fence around the playground Absence of trees and nearby landscaping Empty lots and garbage around the playground Too much sand	PF PF	Plant trees Build up vacant lots around
7. End of the walk	PF	Sun is in the back	PF PF IR UD PF	Not maintained grass Fence Abandoned No building signs No street lights	PF PF PF	Vegetation Shade Fill up empty space

PF = Physical feature; UD = Urban design quality; IR = Individual reactions

Table 15
Vocabulary of thermal meanings extracted from the interview data (N=14). Heat Mappers Walk event. Edison Eastlake Neighborhood

Material	**Thermal meaning**	**Supporting quotes from the interviews**
Asphalt	Very hot	"When I walk my dog, it's like I touch the concrete. I touch the asphalt, and the asphalt is hotter." " It's way hotter because that black asphalt is just more so" "We're walking on cement and then we have asphalt next to us, which is going to be worse."
Metal	Very hot	"it's metal. I'm sure it gets hot" "The sun is literally reflecting off of it. It's probably going to burn my skin, but it's metal. …it's also going to radiate heat the whole time"
Astroturf	Hot	"The Astroturf is…just absorbs heat like crazy." "[…]that the turf gets very hot. There is a community college with one field with Astroturf and another without, and it's night and day. If you've ever played a sport, you know the different between Astroturf and grass." " I've noticed they're much hotter than regular grass, so it's pleasing to look as, but as far as creating a cooler area, I don't think it's effective"
Concrete/ Cement	Cooler than asphalt	"the concrete keeps radiating off it(heat)"
Dirt/ Gravel	Cooler than concrete	"It doesn't feel that hot to me. No, because it's not concrete. It feels like walking in the desert." "It's a hard one because it definitely keeps places cooler, but its not a very good use of water. The trees alone. If they plastered trees all over and more gravel, it would be just as cooler."
Decomposed granite	Cooler than asphalt	" Well, you know, it's that big field of asphalt if it could be you know stabilized decomposed granite or some kind of alternative paving material"
Grass	Cooler	"If I lived here, I would like grass for children and its cooler in the summertime." "People need a small are of grass, it makes you feel like you're in nature."

Individual reactions

Sense of safety

Safety was brought as an important walkability factor. Participants noted the lack of street lights that would make them feel unsafe walking at night. Especially around vacant lots or waiting at the bus stop. Other aspect was feeling vulnerable next to a five-lane road with high traffic volume. Health safety was also a concern. Heat mappers were worried about the health effects of walking in summer and hot surfaces that can cause skin burn, especially for children and dogs: “I always feel really vulnerable when I’m on a major artery like this.”, “Well, I went for two walks with my dog because it was cool. If it’s any more than 80F, I don’t go for walks because it’s too murderous.”, “You can’t really walk your dog unless buying a bunch of gear during the day.”

Sense of comfort

As mentioned earlier, survey responses did not show variability in relation to thermal sensations between the street segments with different infrastructures, however, interviews helped to uncover influential factors. Thermal comfort was one of the structural themes and participants were constantly probed for how comfortable they felt on the walk as well as overall coping strategies to maintain thermal comfort. Participants reported walking more during the cooler months of the year, they would take a longer shadier route as opposed to a shorter one in the sun, and looking for shade was the primary coping strategy: “There’s no shade. At this point, I want to murder someone.”

Sense of community

Seeing people out on the streets and children playing positively influenced overall perceptions of the heat mappers. Strategies for strengthening the community, such as more outdoor activities, village center with amenities, and places for gathering were often brought up.

Sense of ownership

Participants felt uncomfortable walking on the privately owned land or when the land ownership was unclear. Many felt ‘unwelcomed’ walking by the hospital or vacant lots or close to residential courtyards: “Just the comfort you feel like you’re in a developed area rather than an abandoned area.”, “Well I kind of feel like I’m on someone else’s property. I don’t feel like it’s a public space so to speak. You know like it’s for employees of this place. So, I’d feel like I was cheating cutting through here unless it was marked differently.”

Level of interest/pleasantness

Heat mappers felt discouraged walking on streets that did not have visual appeal and active uses on a street. Neighborhood amenities or visual landmarks were common improvement strategies provided by participants.

Discussion

This research has demonstrated complex relationships between the physical environmental conditions under extreme heat and perceptions of walking pedestrians. It became evident that thermal sensations and thermal comfort responses were influenced by both individual reactions and changes in microclimate and infrastructure. Effect of psychological aspects such as thermal history and length of exposure was evident from both the interview and the survey data.

Eliasson et al. suggested that since climate is a moderator of emotional state, than it will also affect aesthetical perceptions.(Eliasson, Knez, Westerberg, Thorsson, & Lindberg, 2007). However, this paper showed that microclimate does not always moderate for the aesthetic perceptions, for instance, segments with same PET values differed on the pleasantness score.

Current research has validated the framework of walking behavior by using the walking interview methodology on a very hot day. Majority of the walkability factors applied in this study. However, participants assessed green and grey infrastructure elements from the point of functionality to mitigate heat. Provision of shade was the most often cited criteria with trees as preferred cooling element for improvement of actual perceptions and as a potential neighborhood retrofit strategy. Participants were explicit about the fact that trees should be functional, meaning strategically planted to provide shade. Palm trees were ruthlessly criticized by most for not providing adequate shade and feeling out of place in the desert environment. Even though, participants had positive perceptions about grass, acknowledging both psychological and physical cooling benefits, majority were willing to make a tradeoff towards xeriscape that was perceived as comparably cool. Other materials and structures were also charged with thermal meanings. Metal and asphalt that is prevalent in many cities was rightfully perceived as very hot and could potentially exacerbate the physical effect of increased PET by adding a layer of negative perception.

These findings lead to several ideas for scientific and practical application: first, thermal comfort models need to be adjusted for thermal perceptions with a varying weight for different shade types and material choices. For example, trees would have a higher positive weight than the metal bus-stop structure. Second, these weights should be practically applied when making decisions about use of materials and structures in hot cities.

Most successful examples of urban ecological planning were done in response to an environmental challenge faced by a city, such as air or water pollution, flooding or landslides and were catalyzed because of fear of destruction, health hazard or legal actions (Spirn, 2006). Extreme heat, which a less visible challenge, but not less dangerous killing more than 1,300 people a year in the U.S ("Climate Change Indicators: Heat-Related Deaths | Climate Change Indicators in the United States | US EPA," n.d.) is also becoming a catalyst for research and action for urban environments (Hartman, n.d.). Spirn argues that successful design, planning and managing of cities requires transformation of perception towards viewing cities as part of the nature and forming landscape literacy, 'the ability to read landscapes', and then developing landscape fluency, 'the capacity for expression'. Understanding environmental phenomena in local urban contexts enables to extract information, analyze, test solutions and make informed public decisions about the urban landscape (Spirn, 2006).

We suggest that developing thermal literacy and thermal fluency is essential for planning and design in hot cities. Cities cannot continue to implement same solutions and use same materials universally disregarding local specificities. Developed vocabulary of thermal meanings could become the first step towards forming thermal literacy. For example, in the case of bus-stop infrastructure, when asked about three bus stops with the same shade structure, only the bus stop with trees was positively perceived by a unanimous choice. In the other two cases, scorching hot sun-exposed benches were impossible to use and the only shade available was behind the shelter. Meaning that for a third of the year, these bus stops are hardly functional. We argue that city infrastructure design standards have to be upgraded towards acknowledging and prioritizing green infrastructure to the other types. Certainly, trees are a kind of a luxury in a desert environment. City struggles with the cost of tree planting, maintenance, and available right of way. However, a basic bus-stop shelter is also costly, between $6,000 and $15,000 (*RPTA Bus Stop Program and Standards. Findings and Recommendations*, 2008). In this case planting a tree and installing the bench can be a far more beneficial and cost effective solution, especially taking into account the added benefits of tree planting ("Parks and Recreation Learn About Phoenix's Urban Forest," 2019). Similar logic should apply to other types of street infrastructure. Infrastructure elements should be tested against the questions: How does it mitigate heat? Does it provide adequate shade? Does this material or object have hot or cool thermal meaning?

Furthermore, even in the hot environments urban design and social factors affecting walkability like feelings of safety, ownership, community and pleasantness were important factors in affecting interviewees' perceptions and cannot be neglected when designing for vibrant and livable cities. To successfully address the challenge of heat it should be a part of multi-purpose solutions addressing social, economic, cultural, and environmental problems (Spirn, 2006).

Opportunities for future research involve expanding the vocabulary of thermal meanings for a wider range of materials and elements that are commonly used in cities, as well as expanding this work to neighborhoods that vary in their infrastructure to compare the differences in thermal perceptions.

Limitations

There is currently a lack of standardization in the methods to assess personal heat exposure, and even more so, subjective aspects affecting perceptions of heat and thermal comfort. This study has attempted to address both, however, had several limitations that should be considered and addressed in the future work. Sample size was limited by the number of interviewers available for the event. Since most of the interviews were conducted one-on-one, it can be difficult to recruit a larger number of interviewers available at the same time, thus, a similar study conducted during a sequence of several days could help to address this issue and increase the sample size. In addition, changes in temperature due to the temporal effect influenced participants' perceptions as they approached the end of the walk. This effect could be minimized if the walk was conducted earlier in the day during the noon hours when the temperatures remain stable for several hours; or by alternating the direction of the walk between the participants.

Another limitation is that interviewed participants did not live in the neighborhood, thus their perceptions may differ from the ones of the residents.

Conclusion

This chapter has used mixed-method approach to evaluate heat related perceptions in relation to the differences in street infrastructure. We identified green and grey infrastructure elements that were positively and negatively perceived and calculated average PET, thermal sensation, thermal comfort and pleasantness score for every street segment and every participant. Modeled PET did not influence subjective perceptions equally, signaling that psychological aspect were involved. Natural elements were perceived most positively. Lack of built infrastructure or lack of shade provided by it was negatively perceived. We have developed a vocabulary of thermal meanings based on the perceptions about materials extracted from the interview data. Furthermore, the study showed that framework of walking behavior previously developed in the literature has to be assessed from the effectiveness of heat mitigation and shade provision when applied to hot and dry cities.

We suggest that outdoor thermal comfort models need to integrate weight depending on the type of mitigation strategy and its psychological perceptions, which should further be applied for designing cities that are more thermally comfortable. We suggest that developing thermal literacy and thermal fluency should be essential to make informed decisions about planning and design in hot cities.

CHAPTER 4

TOO HOT TO WALK? TESTING THE COMPATIBILITY OF OUTDOOR THERMAL COMFORT AND WALKABILITY FRAMEWORKS

Abstract

Cities across the globe are remaking city policies to require or encourage more walking. Yet, achieving walkability in hot and arid cities is challenging. Rising temperatures that make already hot cities even hotter necessitate urgent action for sustainable urban development, part of which is to ensure walkable environments for both GHG reduction and improved health. For this change to be successful, city officials must ensure outdoor thermal comfort for walking. We examined existing research on walkability and outdoor thermal comfort and found that the two areas are not effectively connected. Five articles that considered both aspects were published in the last three years signaling both a gap and an emerging interest in the intersection of walkability and comfort. To improve scientific knowledge on how these two domains can be better connected, we have conducted a meta-review of walkability and outdoor thermal comfort literature, identified methods and main variables for both. Review of methods showed lack of standardization in methods, study designs, and terminology for walkability. Both areas acknowledge the importance of subjective perceptions, however, lack qualitative data and methods to assess these were identified. Variables affecting walkability and outdoor thermal comfort were analyzed and discussed based on similarities, missing links

and conflicts. Finally, guiding questions to ensure walkability and outdoor thermal comfort in hot and dry cities was proposed.

Introduction

> *"because the pedestrian sees, hears, smells, and feels much of the surrounding environment, urban form is likely to play a greater role in the choice to walk"*

(Handy, 1996)

Extreme heat is a growing problem around the world (IPCC, 2014). Already hot urban environments can offer valuable lessons for the warming world. Cities across the globe are investing in massive reconfigurations of downtown and neighborhood environments for walkability, but do not consider thermal comfort. As cities decarbonize through changing development patterns, and promoting non-motorized mobility and public transit, researchers, city officials and designers need an improved framework that promotes walkability and ensures thermal comfort.

Thus, city planners and designers will face the challenge of acquiring and using appropriate knowledge to create both walkable and thermally comfortable pedestrian environments.

In this article, we first review the importance of walkability and thermal comfort for pedestrian urban environments. Then examine existing research on both concepts for similarities and differences. The objective of the paper is to explore existing connections in the literature between walkability and outdoor thermal comfort, compare methods and influencing variables for both and to develop an assessment questions that could guide city planners, designers and policy makers when providing design recommendations hot cities. This chapter draws on the theoretical literature and empirical studies conducted in the previous chapters.

Walkable and Comfortable Pedestrian Environments

The benefits of moderate physical activity, such as walking and bicycling are explored in the public health literature. Thirty minutes or more of accumulated moderate physical activity a day helps to decrease the risk of cardiovascular diseases, asthma, cancer, diabetes, mental health disorders, pulmonary diseases, obesity, and premature death as the result (Frank, Engelke, & Schmid, 2003; Vanos, Warland, Gillespie, & Kenny, 2010). Moreover, improving walkability in cities is a recognized GHG reduction strategy (Edenhofer et al., 2014). Urban morphology is an influential factor on walking behavior. Health, transportation planning and urban design literature have been exploring the qualities of built environment that affect walking behavior from various perspectives and scales (Forsyth, 2015; Southworth, 2005). Transportation literature focuses on macro variables, such as capacity, demand, congestion patterns, regional land use etc. Landscape and urban designers explore the quality of built environment on a microscale and its effect on user perceptions and walking behavior. The importance of these factors is acknowledged but rarely included in the analysis (Southworth, 2005). One definition of walkability that addresses pedestrian experiences is “the extent to which the built environment supports and encourages walking by providing for pedestrian comfort and safety, connecting people with varied destinations within a reasonable amount of time and effort, and offering visual interest in journeys throughout the network" (Southworth, 2005). Even though pedestrian comfort is part of the definition, thermal comfort is rarely specifically addressed in the walkability literature. Importance of weather and climate is sometimes mentioned but implications for walkability are not explored.

Exposure to thermally uncomfortable environment, such as heat, can disincentivize outdoor walking and negatively affect health, exacerbate existing chronic health conditions, and increase heat morbidity and mortality (Harlan et al., 2014; Vanos et al., 2010). For cities in hot and arid climates, maintaining thermally comfortable outdoor conditions for pedestrians can be challenging. Biometeorology literature on outdoor thermal comfort has explored both the effects of urban morphology on microclimate and the physiological aspects of heat exchange between the body and the environment. Scientist also acknowledge the importance of psychological and behavioral factors. That is why an adaptive model of thermal comfort assumes that people adapt to the environment to minimize discomfort and includes three aspects: physiological (body acclimatization to the climate), psychological (expectations in relation to particular environment and thermal history) and behavioral/physical (adjusting clothing, changing posture, using umbrella etc.) (Nikolopoulou & Steemers, 2003; Rupp, Vásquez, & Lamberts, 2015).

Biometeorology literature acknowledges the impact of thermal comfort on walking behavior; however, other aspects related to walkability are not explored from the perspective of extreme weather. In this paper, we argue that to be applicable, the concept of walkability has to be adapted to the stressor of extreme heat. Moreover, resilience literature stresses out the importance to address climate challenges through the lens of SETS framework, which views infrastructure as a socio-ecological-technological system. Such an approach builds awareness towards technological lock-ins, allows identifying of potential tradeoffs, unintended consequences and vulnerabilities, and enables finding adaptive strategies that are not considered under traditional technological framework (Markolf et al., 2018).

Exploring existing connections, review of the literature on walkability and outdoor thermal comfort

To understand connections between walkability and outdoor thermal comfort, this paper systematically reviewed research articles including both terms using Scopus and Web of Science databases. No time constrains were applied.

Search by topic (title, abstract, keyword) ‘walkability’ revealed 1350 and 1526 articles from Scopus and Web of Science respectively. Search by ‘outdoor thermal comfort’ revealed 1585 and 1639 articles from the two databases. Furthermore, results were filtered by search within the articles. Search for ‘outdoor thermal comfort’ or ‘thermal comfort’ in the walkability articles revealed eight articles from Scopus and five from the Web of Science. Similarly, Search for ‘walkability’ within outdoor thermal comfort literature revealed nine articles from Scopus and five articles from the Web of Science. Overall, 14 unique articles that had both terms were retrieved. Out of the 14, one was inaccessible due to language; five were off topic, three articles recognized connections between outdoor thermal comfort and walkability, however, only explored the effect of urban morphology on outdoor thermal comfort and did not consider any other walkability factors. Overall, only five articles explored both walkability and thermal comfort together using different methods at varying scales, from the city to micro level (Table 16). Only one article (Mouada et al.,2019) attempted to correlate microscale urban features related to walkability and thermal comfort perceptions. Majority of the case studies were done in hot and humid or hot and dry climates. Articles were published between 2016 and 2019, signaling a growing interest in intersections between the fields in the recent years.

Table 16

Findings on articles on 'walkability' and 'outdoor thermal comfort' from Scopus and Web of Science databases (N=5)

Articles	Term count	Objective	Site/ Climate	Scale	Methods	Results
Kasim et al. (2018)	TC: 28 W: 6	Identify physical features of the environment influencing pedestrian thermal comfort and microclimate. Evaluate the relationship between thermal comfort and identified features	3 sites across Malaysia/ Humid tropical	Micro	Qualitative assessment 1) Literature review and archival analysis on theories about the physical features influencing thermal comfort. 2)Field study of available features on university campuses 3)Qualitative assessment of available landscape elements combinations, their shading potential and hypothetical effect on pedestrian thermal comfort	Identified four main landscape elements from literature: (man-made shade, pedestrian walkway, seats, trees) and their properties for improved walkability
Mohareb (2016)	TC: 2 W: 4	Investigate the relationships between Jane Jacob's conditions for diversity and GHG emissions comparing Lyon (France), Chicago (Illinois), Kolkata (India), Singapore City (Singapore)	Lyon/ Humid subtropical; Chicago/ Humid continental; Kolkata/ Wet and dry tropical; Singapore City/ Humid tropical	City	1)Review Jacob's conditions for diversity 2)Introduce and explore the history of case study cities 3)A framework for comparison based on population and density; infrastructure development/use; climate and landscape 4)Discuss the relationship between the framework and GHG mitigation	Results showed that conditions for diversity positively affect GHG mitigation. However, differences in development patterns and climate should be considered resulting in individualized GHG mitigation strategies.

O'Brien et al. (2018)	TC: 7 W: 16	Explore the relationships between air temperature and neighborhoods with a varying walkability scores	Montreal/ Humid continental	Neighborhood	Measured air temperature and humidity with a sensor attached to a car and traveling across a variety of neighborhood types Compared recorded temperatures to Walk Scores	Found a strong correlation between the Walk Score and neighborhood scale air temperature
Silva and Akleh (2018)	TC: 9 W: 5	Establish the baseline of the effect of built environment on physical activity. Examine how much exercise is performed outdoors and the effect of seasonal variation on the amount of exercise.	Bahrain/Tropical desert	N/A	International Physical Activity Questionnaire (IPAQ) administered in non-residential areas during two winters and two summers.	Correlation between activity levels and seasonality. Discussed infrastructure changes (land use, urban design, vehicular impact) that could increase physical activity during winter and summer
Mouada et al. (2019)	TC: 21 W: 19	Investigate the relationship between urban morphology, thermal sensations and walking behavior.	Sidi Okba/ Subtropical hot desert	Micro	Measured microclimate variables at eight locations with varying urban morphology. Administered surveys at four times a day during three days in July 2017. Applied walking audit instrument developed from the literature and assigned walkability scores to the studied locations.	Shading, high density and mixed use areas resulted in lower physiological equivalent temperature (PET), thermal sensation vote (TSV) and percent dissatisfied (PPD). Respondents walked faster in sun exposed locations. Preferred walking times were in the morning and in the evening to limit sun exposure.

TC = thermal comfort
W = walkability

Comparing methods between the walkability and outdoor thermal comfort literature

To compare methods used to measure walkability and outdoor thermal comfort we collected review articles on both and extracted most commonly used methods in the two areas. Search terms had to include ‘walkability’ or ‘outdoor thermal comfort’ and ‘review’ in the title. More articles were added from the references of the review publications.

Walkability

Remote sensing, GIS, questionnaire surveys, audits, and indices are commonly used methods to assess walkability (Maghelal & Capp, 2011; Wang & Yang, 2019). Methods can be broadly characterized into two groups. First group characterizes walkability of urban morphology by assigning a number based on scales, levels of service and indices. Second group explores characteristics of built form that either supports or hinders walking by using audits, surveys, and checklists (Maghelal & Capp, 2011). The first group of methods is widely used in transportation planning, the second in the field of landscape and urban design.

There is a variety of indices developed to evaluate the walkability of neighborhoods. Maghelal and Capp identified 85 variables that were used in different combinations to construct 25 indices (Maghelal & Capp, 2011). Walk score and Walk Index are among the most commonly used. Walk Score measures street connectivity, population density, block length, and proximity to neighborhood services (Herrmann, Boisjoly, Ross, & El-Geneidy, 2017). Walkability Index uses actual footpath in calculation versus the road network (Wang & Yang, 2019).

Walkablity researchers acknowledge the importance of both objective and subjective characteristics of built environment, thus, such metrics as imageability, enclosure, human scale, transparency, and complexity are getting more attention to improve walkability (Wang & Yang, 2019). Several scholars have operationalized these metrics (Ewing & Handy, 2009); however, they are still not commonly used (Wang & Yang, 2019).

Outdoor thermal comfort

Measurements of environmental variables, simulations to calculate thermal comfort indices, and survey questioners are used to evaluate outdoor thermal comfort (Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016; Johansson, Thorsson, Emmanuel, & Krüger, 2013). There are several standards and guidelines on how to perform thermal comfort studies, however, there is no consensus on the site selection, number of participants, times of day, seasons, site description etc. (Johansson et al., 2013). Meteorological measurements are performed using stationary and mobile instruments recommended by international standards. Measured meteorological variables that affect thermal comfort include air temperature, short and longwave radiation, humidity, and wind speed (Johansson et al., 2013).

There are more than a hundred existing indices that describe the heat exchange between the body and the environment. Majority were initially developed to measure indoor thermal comfort and were applied for outdoor studies later. There are rational indices, that are calculated using energy balance tools and empirical ones, which are assessed by survey instruments. (Coccolo et al., 2016; Epstein & Moran, 2006; Johansson et al., 2013). Physiologically equivalent temperature (PET) index ,which is defined as the air temperature at which the human body is usually at heat balance indoors and compared to outside conditions, is most commonly used to simulate thermal comfort conditions (Dayi Lai, Liu, Gan, Liu, & Chen, 2019).

Five topics (at 5, 7 or 9 point scale) are widely used to evaluate thermal state of an individual such as thermal perception, thermal comfort, thermal preference, personal acceptability and personal tolerance (Johansson et al., 2013).

Other studies examined psychological factors affecting assessment of thermal comfort, such as perceived naturalness, perceived control of the environment, expectations and thermal history, preferences and culture (Johansson et al., 2013; Knez & Thorsson, 2006; Nikolopoulou & Steemers, 2003). There are currently no standards on how to measure these (Johansson et al., 2013).

Having reviewed the most common methods used to assess walkability and outdoor thermal comfort, several patterns emerged. First, there is a lack of standardization on how to conduct research of this type. A wide variety of scales, sites, used tools and data collecting procedures makes comparisons between studies difficult. Both areas encompass dozens of indices based on different combinations of metrics. This can add unnecessary complexity and confusion on which index to use. Nevertheless, none of these incorporate the whole range of objective and subjective parameters that affect walkability and outdoor thermal comfort. Both areas recognize the importance of subjective evaluations and psychological factors, but robust measuring techniques are yet to come. Moreover, both fields primarily rely on quantitative data and methods. Utilizing qualitative data and mixed methods approach can help with revealing subjective perceptions that affect pedestrian walking behavior and thermal comfort.

Comparing variables related to walkability and outdoor thermal comfort

Variables used to assess walkability and outdoor thermal comfort were extracted through literature meta-review using the same procedure as described above. Variables for walkability and outdoor thermal comfort are presented in Table 17 and 18.

Table 17
Variables affecting walkability extracted through literature meta-review

Variables	**Properties**
Quality of urban form	
Land use mix Residential density Building frontage Landmark buildings Street cafes	Land use mix ad residential density are often used to assess walkability. High scores in these positively affect walkability and were negatively correlated with obesity in numerous studies. Presence of sidewalk cafes and landmark buildings are also related to improved walkability (Maghelal & Capp, 2011; Wang & Yang, 2019)
Street properties	
Street connectivity Number of crosswalks/ intersections Sidewalk availability Width of sidewalk Distance from sidewalk to the edge of the road Number of lanes Street furniture Street lights etc.	Combinations of these street characteristics were identified as variables used in developing walkability indices. Higher quality sidewalks protected from cars positively affect walkability (Maghelal & Capp, 2011; Wang & Yang, 2019)
Access to public transit	Number of public transit stations was used to assess walkability in multiple studies (Maghelal & Capp, 2011; Wang & Yang, 2019)

Urban greening	
Availability of green open spaces Distance to parks Density of street trees	Both street trees and urban parks were positively associated with walkability and reduced obesity levels (Maghelal & Capp, 2011; Wang & Yang, 2019)
Urban design	
Imageability	Imageability is a quality that makes a place recognizable, and is formed by particular arrangements of physical features or their unique characteristics, for example landmark buildings (Ewing & Handy, 2009; Wang & Yang, 2019)
Enclosure	Enclosure is defined by the presence of vertical elements on the street, such as buildings, trees, street lights, etc. (Ewing & Handy, 2009; Wang & Yang, 2019)
Human scale	Human scale is defined as proportion of physical features to the size of the human. It also relates to human speed versus speed of other street objects, such as cars (Ewing & Handy, 2009; Wang & Yang, 2019)
Transparency	Transparency is defined by visible human activity seen beyond the street. Windows, doors, and fences that allow visibility increase transparency (Ewing & Handy, 2009; Wang & Yang, 2019)
Complexity	Complexity characterizes visual richness of the street. It can be enhanced by various physical features, such as buildings, trees, landscaping, street furniture, etc. (Ewing & Handy, 2009; Wang & Yang, 2019)
Safety	Safety from traffic and street crime is positively associated with walkability (Maghelal & Capp, 2011; Wang & Yang, 2019)
Comfort/Convenience	
Topography Weather/Climate Shade and rain cover Street furniture and landscaping Odor Noise Crowding etc.	Objective and subjective factors found in walkability literature (Maghelal & Capp, 2011; Wang & Yang, 2019)

Table 18
Variables affecting outdoor thermal comfort extracted through literature meta-review

Variable	Properties
Urban geometry	
Aspect ratio	Defined as street canyon height to width ratio. High aspect ratio results in lower daytime and higher nighttime air temperatures. Higher aspect ratio increases shading and results in significant reductions in PET. Deep canyons may trap the air flow lowering the wind benefits on thermal comfort (Jamei, Rajagopalan, Seyedmahmoudian, & Jamei, 2016; Dayi Lai et al., 2019)
Street orientation	E-W streets are the most challenging in terms of outdoor thermal comfort. NE-SW and N-S orientations are more beneficial for hot climates. There is no preferred orientation for streets with tall buildings (Jamei et al., 2016; Dayi Lai et al., 2019)
Sky view factor (SVF)	Defined as the ratio of the sky that can be visible from a given point to the available portion. Low SVF results in lower daytime and higher nighttime air temperatures and PET (Jamei et al., 2016; Dayi Lai et al., 2019)
Type and form of urban morphology	Compact urban forms are considered most beneficial for hot climates because they limit sun exposure (Jamei et al., 2016; Dayi Lai et al., 2019). Compact forms may result in wind trapping; however, in hot climates influence of shade on thermal comfort outweighs the disadvantages regarding reductions in wind speed (Lai et al., 2019)
Materials	
White (reflective) roofs	White roofs reflect short wave radiation and result in air temperature reductions. It is a beneficial urban heat island mitigation strategy. On a microscale level, the strategy is effective for low-rise buildings, cooling effect diminishes with increased building height (Dayi Lai et al., 2019; Nouri, Costa, Santamouris, & Matzarakis, 2018)
Reflective pavements	Reflective materials reduce surface and air temperature. However, highly reflective surfaces may increase PET resulting in higher pedestrian discomfort. Highly absorptive pavements, such as dark asphalt also increase discomfort due to high heat emittance. There is no consensus in the literature on the paving material type for optimal thermal comfort (Dayi Lai et al., 2019; Nouri et al., 2018)
Urban greening	
Street trees	Street trees reduce solar and terrestrial radiation and thus positively affect thermal comfort. Their effectiveness depends on several characteristics, such as height, geometry of the canopy, characteristics of the foliage, leaf index, and maturity level. Irrigation and leaf temperature influences the cooling effect of the trees. Cooling effect from trees is diminished in the deep street canyons (Jamei et al., 2016; D Lai, Liu, Gan, Liu, & Chen, 2019)

Urban parks	Urban parks are known for 'park cool island' phenomena, when the air temperature in the park is much lower than in other parts of the city. One study found that parks can be up to 12C cooler. The cooling effect depends on the size and structure of the park, type of plants used, level of sky obstruction, and irrigation frequency. The extent of the cooling effect on other areas of the city depends on the proximity of that urban area, wind direction and elevation. In general, larger parks have a bigger effect (Dayi Lai et al., 2019; Nouri et al., 2018)
Green roofs	Green roofs on high-rise buildings have negligible effect on thermal comfort at a pedestrian level. However, buildings with the height under 10 meters can result in air temperature reductions at pedestrian level, and, thus, improve thermal comfort (Dayi Lai et al., 2019; Nouri et al., 2018)
Green walls	Cooling effect of green walls depends on the outdoor air temperature. The highest reductions are achieved on the hotter days (Dayi Lai et al., 2019; Nouri et al., 2018)
Water features	
Water bodies	Water bodies act as heat sinks in urban environment and can improve thermal comfort by lowering air temperature and PET. Cooling effect depends on wind direction and distance from urban areas. The effects of water on humidity levels are not explored. Presence of water was associated with higher perceived comfort in hot and arid climates (Dayi Lai et al., 2019; Nouri et al., 2018)
Misting	Misting systems reduce air temperature by increasing relative humidity, thus, this strategy is more effective in hot and dry climates. Studies found that for 1C reduction in air temperature there is a 5% increase in relative humidity. Cooling effect depends on the amount of sprays and size of particles (Nouri et al., 2018)
Psychological factors	
Naturalness	Naturalness is defined as an environment free from artificiality. Research shows that people can better tolerate changes that are produced naturally (Dayi Lai et al., 2019; Nikolopoulou & Steemers, 2003)
Expectations	Expectations determine what the environment should feel like in relation to the season or previous days (Dayi Lai et al., 2019; Nikolopoulou & Steemers, 2003)
Short and long-term experience	Experience influences the expectations. Short-term experience is affected by day-to-day changes in weather. Long-term experience is influenced by the schemata of actions constructed in the brain in relation to the environmental conditions (Dayi Lai et al., 2019; Nikolopoulou & Steemers, 2003)
Time of exposure	Time of exposure may change the perception of thermal comfort. Short exposure to uncomfortable conditions is less likely to be perceived negatively (Dayi Lai et al., 2019; Nikolopoulou & Steemers, 2003)

Perceived control over the environment	People feel more comfortable when their perceived control over the environmental situation is higher. Authors showed that people who had a choice between sun and shade reported higher thermal comfort levels even though they did not adjust their location. Similarly, people who had to be in a particular place, for example waiting for someone, felt less comfortable than people who chose to be in that place for other reasons (Dayi Lai et al., 2019; Nikolopoulou & Steemers, 2003)

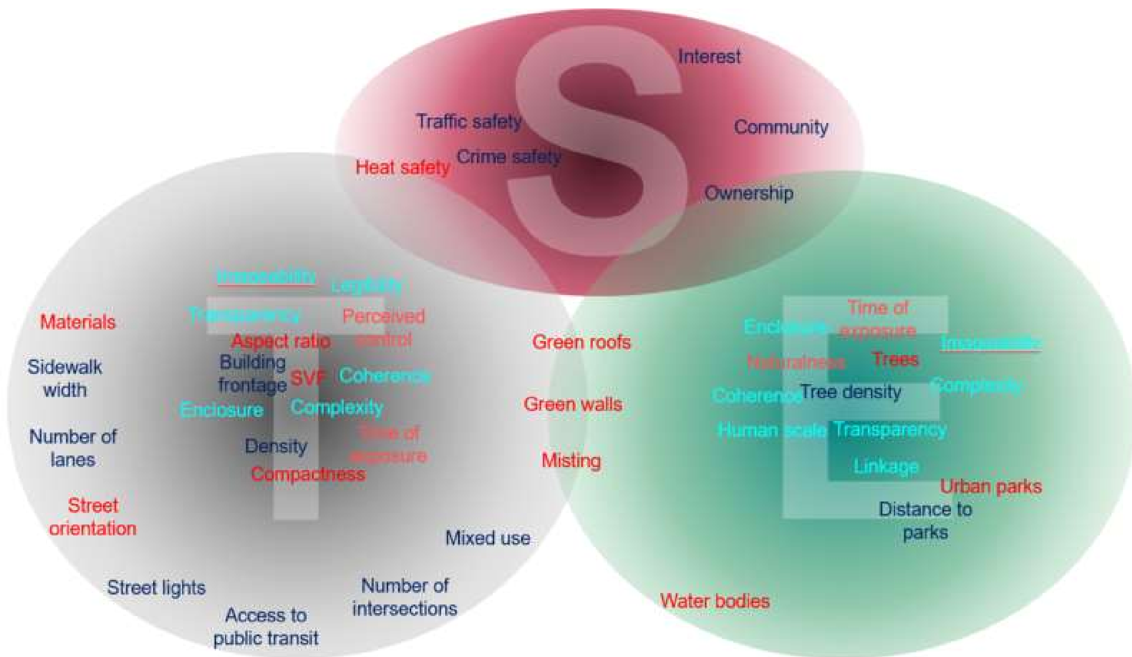
Several patterns emerged after compiling the variables influencing walkability and outdoor thermal comfort. For instance, there is a lack of standardized practices to assess urban environment and wide heterogeneity of variables associated with walkability. Those factors are often not tested for their aggregated effect on walking and may differ depending on communities and cultures (Maghelal & Capp, 2011; Wang & Yang, 2019). Walkability variables compiled in Table 17 present some of the most commonly used, but the list is not exhaustive and terminology and groupings differ across literature. For instance, one study that evaluated 25 pedestrian indices compiled 85 variables, including both objective, subjective and site specific variables (Maghelal & Capp, 2011). Other study compiled frameworks that study urban design quality with more than a 100 different variables related to walkability (Hooi & Pojani, 2019). Many variables describe same features of urban environment, but utilize slightly different terminology or assessment methods. Few studies examined demographics, economic and psychological factors. However, scientist agree that subjective evaluations are important (Wang & Yang, 2019).

Variables for outdoor thermal comfort in relation to physical properties of the built environment are well established in the literature, even though measurement procedures differ across studies. Variables regarding materials and water features are limited and require more investigation. In both realms, psychological and subjective evaluations are acknowledged as important but rarely operationalized or included in the models.

Analysis and discussion

Variables were organized through the lens of a Social-Ecological-Technological Systems (SETS) framework (Figure 29). SETS implies that infrastructure is a product of the interactions of social, ecological and technological systems and SETS lens has to be adopted when developing strategies to increase resilience of cities to intensifying weather extremes (Markolf et al., 2018).   Walkability and outdoor thermal comfort variables that relate to similar physical features were grouped closer to each other towards the center of the domains. Variables at the edges did not have similar equivalents and were located at the edges.

Variables were qualitatively assessed for connections, missing links presenting opportunities and potential conflicts with the consideration of extreme heat as the main stressor.



Dark blue: walkability variables related to physical features; light blue: walkability variables related to urban design; dark red: outdoor thermal comfort variables related to physical features; light red: outdoor thermal comfort variables related to psychological evaluations

Figure 29
Walkability and outdoor thermal comfort variables organize through the lens of SETS

<u>Existing connections:</u>

Building geometry

Various characteristics of built form were addressed in both walkability and outdoor thermal comfort literatures. Walkability literature metrics like building frontage, defined as the distance of building from end of sidewalk, as well as subjective design qualities such as enclosure and complexity can be enhanced by established metrics from

outdoor thermal comfort literature such as aspect ratio and sky view factor to optimize shade patterns and enhance urban design qualities at the same time.
Techno-ecological solutions like green walls and misting systems examined in outdoor thermal comfort literature have potential to enhance perceived naturalness as well as to add distinct features to the built form enhancing imageability and human scale.

Urban greening

Trees are present as an important variable in both realms. Walkability literature examines tree presence, density or number of street trees. However, in hot climates, caution must be taken as what types of trees are used and whether they are functional for shade. Chapter 3 revealed that study participants had negative opinions about trees that did not have potential to provide shade. Outdoor thermal comfort literature provides specifics on optimal tree characteristics such as height, shape of the canopy, leaf index and maturity. Trees are positively linked to subjective perceptions in both walkability and outdoor thermal comfort, affecting perceived naturalness, time of exposure, control of the environment, as well as complexity, and imageability qualities of the street environment. Similarly, urban parks are present in both literatures. Distance to parks or access to parks positively affects walkability. Urban parks are known for the 'park cool island'. However, this effect is dependent on the size of the park, types of vegetation, irrigation patterns location in regards to wind and proximity to urban areas.

Missing links:

Land use

Availability of mixed uses and neighborhood amenities is one of the main factors influencing walkability. However, this variable is not explored in the outdoor thermal comfort literature. We believe that there is a potential for linkages between the two. A concept of 20-minute city, when one can access all the necessary services by walking for not more than 20 minutes, appears as a goal of many modern cities, like Portland, Melbourne, and Tempe (City of Portland, 2019; City of Tempe, 2013; State Government of Victoria, 2016). However, in hot climates even a 20-minute walk is a challenge. Careful planning and positioning of mixed uses along the walking routes can offer relieve from heat and break down a 20-minute walk in to shorter 5-minute intervals. Thus, indoor amenities have to be scrutinized by the type of use and whether they add diversity to the existing ones, time that visitor is expected to spend there, populations who can use the service, financial resources required to enter, proximity to public transit stop, etc. These can vary from fixed indoor amenities to semi-permanent and mobile ones. An example of semi-permanent service is a mini-store with climate control at the bus stop; a mobile use can be a bicycle cart that circulates around the neighborhood offering refreshments for pedestrians. Interventions like this have potential to affect time of exposure, thermal history and provide more control of the environment for pedestrians, which are all important psychological aspects of outdoor thermal comfort.

Street infrastructure

Different characteristics of street infrastructure were found in walkability literature. Number of intersections, number of car lanes, streetlights and street furniture not only affect walking behavior, but are equally important for outdoor thermal comfort in hot climates. Lack of intersections and streetlights can increase time of exposure and busy roads with many car lanes can add waste heat exacerbating thermal conditions.

Access to public transit

Number of transit stops is one of the variables that affect walkability. Transport and health literature has found that populations who use public transit have increased exposure and vulnerability to heat (Fraser & Chester, 2016; Karner, Hondula, & Vanos, 2015). Effective public transit system can positively affect walkability in hot climates in a similar way to mixed use by providing a temporary heat relief, resetting thermal history and reducing time of exposure.

Street orientation

Street orientation is an important variable of outdoor thermal comfort not explored in walkability literature. Findings from Chapter 3 suggest that position of the sun in relation to participant was affecting their perception of the streets, and thus, walkability for hot climates should consider street orientation to ensure maximum comfort. As shown in Table 18, N-S or NE-SW orientations a preferable, however, since street orientation can rarely be altered, increasing building height for less favorable E-W orientations can improve pedestrian comfort. Ali-Toudert and Mayer found that arcades can be effective in improving PET at E-W streets (Ali-Toudert & Mayer, 2007).

Materials

Materials is another area that deserves more attention for walkability in hot and dry climates. Results from Chapter 2 and Chapter 3 revealed that many materials commonly used in urban settings might not be comfortably walkable and safely touchable in hot climates for a wide portion of the year. On top of that, they may have negative thermal meanings adding to the perceived discomfort and inhibiting walkability. Physical qualities and thermal perceptions can be altered by relatively easy fixes, for example, one study found that that darker or lighter color of the same paving material, for example granite or asphalt can result in significant temperature reductions (Djekic, Djukic, Vukmirovic, Djekic, & Dinic Brankovic, 2018).

Water elements

The effect of water bodies or urban water features is not well studied; however, it is a promising direction to not only improve outdoor thermal comfort, but also to boost urban design quality of the space adding to imageability and complexity aspects. Desert cities like Phoenix and Tempe embraced misters to improve thermal comfort of outdoor venues and even piloted a misted bus stop. There is still lack of scientific evidence on the performance of these technologies.

Safety

Safety from traffic accidents and crime is addressed in the walkability literature. Chapter 3 showed that personal heat safety, as well as safety for of children and dogs when walking and playing outdoors was a concern for majority of study participants, and should be integrated into walkability framework in hot climates.

Conflicts

Street length

Short blocks with many intersections are the variables that positively affect walkability. However, this strategy has to be used together with other traffic control measures, as more intersections can result in increased idling, waste heat and GHG emissions (Mohareb, Derrible, & Peiravian, 2015).

Density

Compactness and density appear as positive variables in both walkability and outdoor thermal comfort literature by offering shade and enclosure. Nevertheless, dense urban environments are known for urban heat island effect (Oke, 2011). Study in Montreal, Canada, showed that neighborhoods with a higher walk score had higher air temperature (O'Brien, Ross, & Strachan, 2019). Even though air temperature is one variable affecting human thermal comfort, it has a lesser effect than direct solar radiation. Greater reductions in PET can be achieved by providing shade than reducing air temperature by a few degrees. For this reason, we believe that when designing for walkability in hot and arid cities, provision of shade should be a priority.

Assessment questions to ensure walkability and outdoor thermal comfort for hot and dry climates

Ensuring walkability in extreme heat is no easy task. Research shows that cities with extreme climate challenges are inclined towards using cars over non-motorized mobility and public transit (Mohareb et al., 2015). Nevertheless, thermal comfort aware planning, design and policies can help to reverse the trend. Such an approach requires exploiting currently weak or non-existing links between walkability and outdoor thermal comfort and minimizing potential conflicts. This is something that cities need to be conscious about when setting design policies and recommendations. For example Los Angels' undertaking to paint asphalt with reflective paint ("Cool Pavement Pilot | Bureau of Street Services," 2017) may cause even greater pedestrian discomfort , since increased surface reflectivity can negatively affect PET (Dayi Lai et al., 2019; Taleghani, 2018); Phoenix Walkable Urban Code encourages use of alternative paving materials, with granite and flagstone among them (City of Phoenix, 2019). However, flagstone and black granite had the highest surface temperatures among all paving materials when tested for one summer in a city of Nis, Serbia (Djekic et al., 2018).

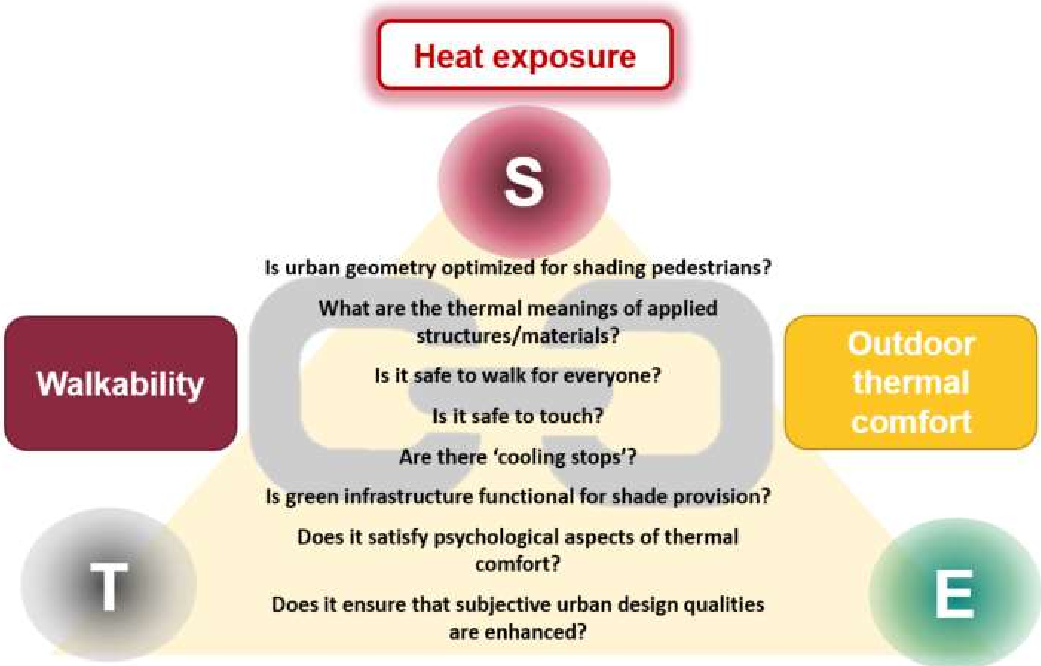


Figure 30
Assessment questions to assist in implementing design solutions and policies that simultaneously address walkability and outdoor thermal comfort in hot and dry climates

To minimize unintended consequences when making decisions about urban form, we suggest an assessment framework (Figure 30) with guiding questions aimed to ensure that socio-ecological-technological systems are resilient to extreme heat and provide walkable and comfortable outdoor spaces. Scientific literature and empirical studies from the previous chapters show that both objective and subjective aspects of walkability and thermal comfort are essential to support walking in hot cities.

Future research directions could concentrate on validating the framework through empirical studies; develop instruments that can better capture subjective evaluations of the environment in relation to personal comfort; adapt the framework to hot and humid climates.

CHAPTER 5

CONCLUSION

Summary

The purpose of this dissertation has been to argue for the need of integration of subjective assessments in outdoor thermal comfort modelling; and prioritizing outdoor thermal comfort when designing for walkability in hot and dry cities. A desert city Phoenix, Arizona, was used as the case study to explore the effects of street infrastructure on bus riders and pedestrians during the hottest periods of the year. Results and methods used in this study may assist mitigating the effects of urbanization and global warming in hot cities.

The major findings from each chapter are presented below, followed by the main contributions and directions for the future research.

Chapter 2 explored outdoor thermal comfort of bus riders at bus stops with different infrastructure types in one Phoenix neighborhood. To assess thermal comfort, microclimate measurements were taken simultaneously with surveys of bus riders waiting at the stops. Analysis of the effectiveness of different shade types (tree, bus stop shelter, vegetated awning, and advertising sign) revealed that trees are most effective for air temperature reductions, with the mean difference of 1.37 °C comparing to the sun exposed locations. Air under the bus-stop shelter was on average cooler by 0.66°C. For globe temperature, which resembles the thermal conditions felt by the human body, advertising shade provided the highest reductions of 8.78°C, followed by tree shade with 8.45°C and bus shelter shade with 7.98°C.

Analysis of surface temperatures showed that maximums for sun-exposed surfaces of all tested material types by far exceeded the 44°C threshold sufficient for a skin burn at a prolonged exposure. However, shade helps to reduce the temperatures by as much as 20°C and minimizes temperature differences between different material types. Notably, the highest reductions were achieved at noon and afternoon, where temperatures were the highest.

Survey data showed that almost half of bus riders felt very hot or hot, and more than a half experienced a certain degree of thermal discomfort. Psychological variables were significant in affecting thermal comfort, for instance even though only three people were under the tree when they were surveyed, about the same amount of people selected trees as important for cooling. Moreover, upgraded stops were perceived as more beautiful and beauty affected improved thermal sensations. Hydration and seeking shade were the preferred coping strategies while walking and waiting at the bus stop

Chapter 3 examined how streets with different types of infrastructure affect perceptions and thermal comfort of pedestrians, and whether framework of walking behavior found in the literature applies in the hot and dry climate. The Heat Mappers event conducted in one of the most heat vulnerable Phoenix neighborhoods was used as a case study. Participants walked predetermined route on a hot afternoon, filled out a field guide and were interviewed along the way. Microclimate measurements were collected with a mobile human-biometeorological station (MaRTy); GPS data was collected for every participant and joined with MaRTy data to calculate physiological equivalent temperature (PET) for each street segment.

Survey results on participants' thermal sensation vote, thermal comfort and street pleasantness showed that there was a higher variation between individual participants than between the street segments. However, perception of street pleasantness was more strongly attributed to particular street segments. PET results were mapped using GPS data. The street segment with the highest mean PET temperature of 49.2°C was the vacant land on the west side of the neighborhood, followed by the arterial road with sparse commercial developments. The lowest was the segment with two-story residential development with the mean PET 44.3°C, followed by the last segment leading back to the park, which is likely attributed to the afternoon cooling effect. One-story residential development with large trees and grass were selected as the most pleasant segment and had a mean PET of 45.7°C.

Analysis showed that the framework of walking behavior developed by Ewing and Hardy (Ewing & Handy, 2009) applied in the hot and dry conditions; however, participants assessed it from the point of heat mitigation. Participants assessed green and grey infrastructure based on its shade provision and thermal perceptions. Natural elements were generally positively perceived and lack of infrastructure was perceived as negative. In addition, vocabulary of thermal meanings for materials was compiled from the participants' reactions.

Finally, in Chapter 4 guiding questions to address walkability in hot and arid cities were developed. First, a systematic literature review showed that there are insufficient connections between the fields of walkability and outdoor thermal comfort. From the two databases with more than 3000 articles in total, only five articles addressed both walkability and thermal comfort as the primary or secondary objective. Comparison of methods between the two areas showed a wide variety of indices that exist for both do not include subjective evaluations, even though both fields acknowledge their importance. Furthermore, there is a lack of standardization on the research practices, and both fields mainly rely on quantitative methods.

Both walkability and outdoor thermal comfort literature include subjective variables, such as imageability, enclosure, human scale, transparency, complexity, for walkability; and naturalness, expectations, short and long-term experience, time of exposure, perceived control of the environment for the outdoor thermal comfort. However, there are no clear methods to explore these. Analysis of the variables through the lens of SETS framework revealed the overlaps, missing links and potential conflicts between the variables used for assessing walkability and outdoor thermal comfort. Based on that analysis, a set of guiding questions was developed to address the walkability in hot and dry climates that may be useful for researchers and practitioners in the field of urban design and heat mitigation.

Contributions

This dissertation has contributed to understanding outdoor thermal comfort in hot and dry cities at a pedestrian level. Complex interactions between people and environment were uncovered through exploring both objective and subjective perceptions with a mixed methods approach using a variety of data sources.

The conducted studies showed that current bus stop infrastructure in Phoenix is not effective in providing thermal comfort in the summer months. Tress were most effective in providing both physiological thermal comfort through reductions of air and globe temperature; and psychological since they were often perceived beneficial for cooling. Vegetated awnings present at several stops, a seemingly promising solution to provide thermal comfort and introduce art with natural elements, poorly performed for air and globe temperature reductions. This fact can be explained by the scarcity of vines due to the lack of maintenance, an issue the city has to face because of the complexities involved in coordinating separated departments responsible for installation, maintenance, and limited financing. Heat safety of metal bus-shelters with maximum surface temperatures exceeding 60°C is highly questionable. Moreover, other elements such as trees and advertising were more effective in reducing air and globe temperature, showing that design and material choice of standard bus-stop shelters is not optimized for thermal comfort. The fact that advertising signs provided highest reductions in the globe temperature signifies importance of the solid vertical shade that is not integrated in current design.

This research contributes to understanding thermal perceptions of walking individuals on city streets. It was clear that shade and infrastructure that provides or stimulates clear thermal sensations or perceptions were valued the most. Unfortunately, most common infrastructure and material choices are inadequate to satisfy these.

Considering the high cost and poor thermal performance of basic infrastructure, hot and warming cities need to rethink guidelines and standards for infrastructure provisions, prioritizing thermal comfort and natural solutions. To ensure that cities can provide thermal comfort in the context of rising temperatures, stakeholders involved in planning and design of cities need to develop thermal literacy and thermal fluency. Integration of scientific findings on physical properties of urban environments together with subjective perceptions of actual users can help to achieve this goal.

This dissertation helps to shorten the gap of the effect of subjective evaluations in relation to outdoor thermal comfort and walkability by using mixed methods approach and combining quantitative and qualitative data. A variety of thermal comfort measurement devices with survey instruments and semi-structured walking interviews were used to unravel the interactions between physical and psychological interactions. Furthermore, this study helps to strengthen the links between the walkability and outdoor thermal comfort. Weakly connected variables such as mixed use or materials offer potential for improvements in both areas. Identified conflicts may assist to avoid unintended consequences when designing for both walkable and thermally comfortable cities.

Finally, this dissertation provides an assessment framework with guiding questions aimed to ensure that socio-ecological-technological systems are resilient to extreme heat and provide walkable and comfortable outdoor spaces.

Future research directions

Opportunities for future research could involve validating the framework for walkability in hot and dry climates in the neighborhoods that differ in their social, ecological and technological conditions; and expanding the vocabulary of thermal meanings to include a comprehensive list of materials and public infrastructure features that could be used in cities.

Moreover, future research could expand this work to cities that face similar climate challenges. For instance, many cities of the Global South are currently developing their public-transit infrastructure systems and wish to avoid falling into the auto-dependency trap that has characterized development patterns in much of the Global North. It is important to examine current public transit and thermal-comfort conditions in developing cities with climate challenges, to offer alternative development scenarios for sustainable mobility. One example is another city in the Sonoran desert, Hermosillo, Mexico. While having similar to Phoenix climate conditions, Hermosillo differs in its social, ecological and technological systems and how they interact. The city is currently undergoing the changes in its public transit system and urban development and would benefit from studies that explore current thermal conditions and infrastructure systems that provide the most benefit.

Moreover, even though this study has concentrated on developing a walkability framework for hot and dry climates, the next step is to extend it to hot and humid climates and explore the similarities and differences. It is likely that many principles will apply, however, there likely will be differences in which variables should be prioritized and how they would affect thermal perceptions, for example while urban green can be less of a challenge in a tropical climate, airflow may become more influential.

Even though heat is becoming a universal challenge, every city is experiencing it in a different way, and as scientists, we must ensure that we provide a wide range of studies that address these differences and provide recommendations that are accessible to stakeholders for a successful mitigation of urban heat and improved livability of cities.

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APPENDIX A

BUS-STOP SURVEY INSTRUMENT

To be filled out by survey administrator
Team member name: __________
Bus stop ID#: ______________

ARIZONA STATE UNIVERSITY

City of Phoenix Bus Stop Survey, Summer 2018

ASU research team requests your help in understanding public transit riders' experiences at Phoenix bus stops. Please complete the following questions to the best of your ability. All answers are optional. Thank you for your time.

1. How did you reach this bus stop?

☐ Walking ☐ Biking ☐ In a vehicle ☐ Transferred from another bus ☐ Other: ______

2. How long did it take you to reach this bus stop?

☐ 1-5 minutes ☐ 6-10 minutes ☐ 11-15 minutes ☐ 16-20 minutes ☐ Over 20 minutes

3. How long do you typically wait at this bus stop?

☐ 1-5 minutes ☐ 6-10 minutes ☐ 11-15 minutes ☐ 16-20 minutes ☐ Over 20 minutes

4. Do you do any of the following when it gets hot? Select all that apply.

☐ Earlier/later travel ☐ Bring an umbrella ☐ Bring water or bring more water

☐ Rideshare/cab ☐ I try to get shade cover on the way ☐ Go to another stop with more shade

☐ I don't change my behavior ☐ Other: ______________

5. What do you usually do while you are at a bus stop when it's hot? Select all that apply.

☐ Seek shade ☐ Sit ☐ Look around ☐ Use phone ☐ Hydrate ☐ Eat ☐ Socialize

☐ Listen to audio ☐ Read ☐ Other: ________

6. Do any of these elements make you feel cooler? Select all that apply.

☐ Nearby trees ☐ Nearby grass ☐ Nearby shrubs ☐ Benches ☐ Shade Structures

☐ Nearby drinking water fountain ☐ Other: __________________

7. What is your perception of this bus stop?

☐ Unpleasant ☐ Slightly unpleasant ☐ Neutral ☐ Slightly Pleasant ☐ Pleasant

8. Do you think this bus stop is:

☐ Ugly ☐ Somewhat ugly ☐ Neutral ☐ Somewhat beautiful ☐ Beautiful

9. How do you feel at this bus stop?

☐ Very Cold ☐ Cold ☐ Cool ☐ Slightly Cool ☐ Neutral ☐ Slightly Warm ☐ Warm ☐ Hot ☐ Very Hot

10. My current level of thermal comfort is:

☐ Comfortable ☐ Slightly Uncomfortable ☐ Uncomfortable ☐ Very Uncomfortable

Personal background:

Using this bus stop is part of my daily routine: ☐ Yes ☐ No

I have lived in Phoenix for: ☐ Less than 3 months ☐ 3 months to 1 year ☐ 1-3 years ☐ 3+ years

Do you own a vehicle? ☐ Yes ☐ No

Reason for trip: ☐ Work/School ☐ Family/friends ☐ Recreation ☐ Errands/shopping

☐ Other: ___________

Household income:

☐ Below $20,000 ☐ $21,000-$30,000 ☐ $31,000-$40,000 ☐ $41,000-$60,000

☐ $61,000-80,000 ☐ $81,000-$100,000 ☐ Over $100,000

Age: ☐ 18-25 ☐ 26-35 ☐ 36-50 ☐ 51-65 ☐ 65+

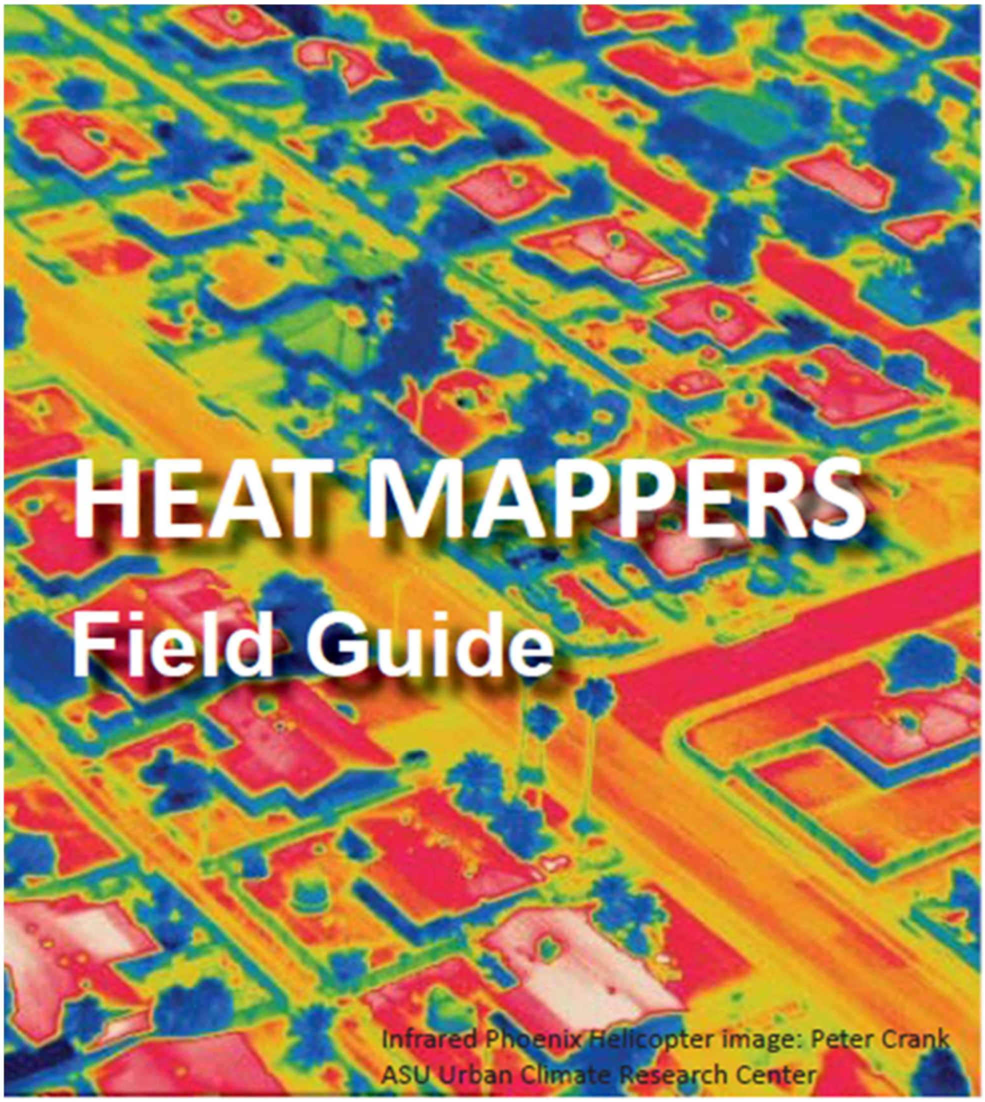
Is there anything else you'd like to tell us about bus stops in Phoenix?

Thank you very much for taking the time to complete this survey. Your feedback is valued and very much appreciated!

APPENDIX B

HEAT MAPPERS FIELD GUIDE SURVEY AND GUIDING WALKING INTERVIEW QUESTIONS

Heat Mapper Field Guide Survey Instrument developed for the Heat Mappers event



The Nature Conservancy
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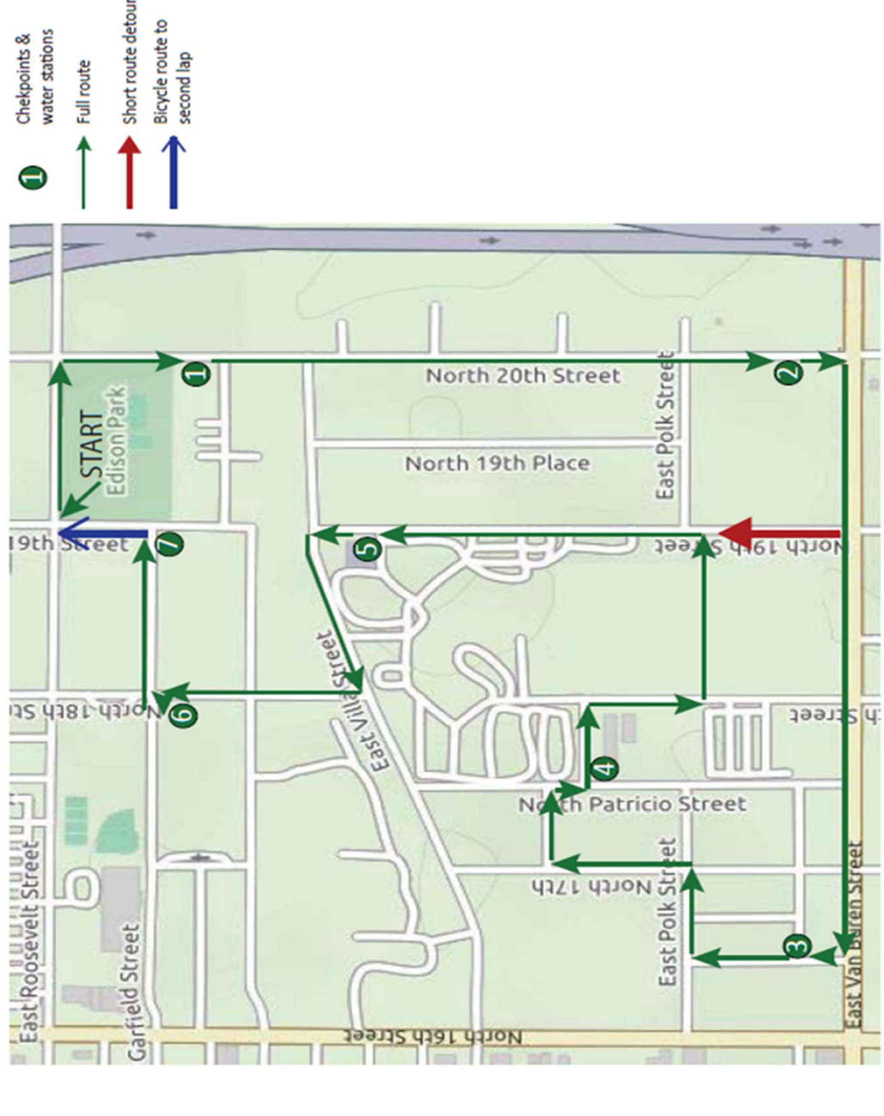
NATURE'S COOLING SYSTEMS PROJECT

MoW

ASU Urban Climate Research Center
Arizona State University

ASU Knowledge Exchange for Resilience
Arizona State University


Chekpoints & water stations
Full route
Short route detour
Bicycle route to second lap
START
Edison Park
North 20th Street
North 19th Place
East Polk Street
19th Street
East Villa Street
North Patricio Street
North 17th
East Van Buren Street
East Roosevelt Street
Garfield Street
North 16th Street
1
2
3
4
5
6
7

Basic Participant Information

(Please circle your answer)

Q1. What is your age?

18-24   25-44   45-64   65 or older

Q2. What is your sex?

Male   Female   Do not identify as male or female

Q3. Do you live in the Edison-Eastlake neighborhood?

Yes   No

Q4. How would you describe your health?

Excellent   Good   Fair   Poor

Q5. In the summer months, how much time do you spend outside, on average?

More than 2 hours per day   1-2 hours per day   1 hour to 30 min. per day   Less than 30 min. per day

*Q6. How serious are the risks posed by **normal summer temperatures** to you and your household?*

Not at all serious   Not too serious   Somewhat serious   Very serious   Extremely serious

*Q7. How serious are the risks posed by **extreme heat** to you and your household?*

Not at all serious   Not too serious   Somewhat serious   Very serious   Extremely serious

*Q8. How serious are the risks posed by **sun exposure** to you and your household?*

Not at all serious   Not too serious   Somewhat serious   Very serious   Extremely serious

Q9. This past summer, did you have any health symptoms related to heat or high temperatures, such as leg cramps, dizziness, fatigue, fainting, rapid heartbeat, hallucinations, or heat stroke?

Yes   No

Get Ready to Go!

Q1. Will you be walking or biking today's course?

Walking   Biking

Q2. What is the best way to describe the clothes you are currently wearing?

Shorts and a short sleeve shirt   Long pants and a short sleeve shirt   Long pants and a long sleeve shirt

Q3. Will you be using any of the following items during the walk? (circle all that apply)

Hat   Sunglasses   Umbrella   Sunscreen   Water bottle

Q4: Currently I am:

In full sun   In full shade   In a mix of sun and shade

Q5. At this moment, I am:

Very cold   Cold   Cool   Slightly cool   Neutral   Slightly warm   Warm   Hot   Very hot

Q6. My current level of thermal comfort is:

Comfortable   Slightly uncomfortable   Uncomfortable   Very uncomfortable

Stop #1:

On 20th street, south of the Edison Park

Q1. What is one or a few words you would use to describe the stretch we have just walked?

Q2. Since the start, what percent of the route was covered by shade? Make your best guess.

Q3. You are at the corner of Edison Park. How often do you use parks in Phoenix in summer months?

Almost every day | Every week | Few times each summer | Never

Q4. If you could make one change to this park what would it be?

Q5: Currently I am:

In full sun | In full shade | In a mix of sun and shade

Q6. At this moment, I am:

Very cold | Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot | Very hot

Q7. My current level of thermal comfort is:

Comfortable | Slightly uncomfortable | Uncomfortable | Very uncomfortable

Q8. My perception of the street segment I just walked is:

Unpleasant | Slightly unpleasant | Neither pleasant nor unpleasant | Slightly pleasant | Pleasant

Stop #2:

On 20th street, north of Van Buren

Q1. What is one or a few words you would use to describe the stretch we have just walked?

Q2. Since the last stop, what percent of the route was covered by shade? Make your best guess.

Q3: Currently I am:

In full sun | In full shade | In a mix of sun and shade

Q4. At this moment, I am:

Very cold | Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot | Very hot

Q5. My current level of thermal comfort is:

Comfortable | Slightly uncomfortable | Uncomfortable | Very uncomfortable

Q6. My perception of the street segment I just walked is:

Unpleasant | Slightly unpleasant | Neither pleasant nor unpleasant | Slightly pleasant | Pleasant

Pay attention to the bus stops on your walk towards your next checkpoint

Stop #3:
On 16th place, north of Van Buren

Q1. What is one or a few words you would use to describe the stretch we have just walked?

Q2. Since the last stop, what percent of the route was covered by shade? Make your best guess.

Q3. On Van Buren Street, we walked past three bus stops. Which one seemed preferable to wait at?

The first one we passed | The second one we passed | The third one we passed | They seemed about the same

Q4: Currently I am:

In full sun | In full shade | In a mix of sun and shade

Q5. At this moment, I am:

Very cold | Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot | Very hot

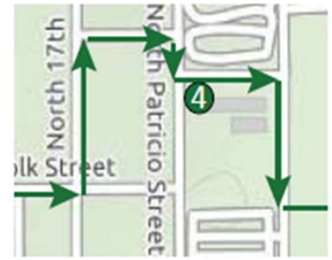
Q6. My current level of thermal comfort is:

Comfortable | Slightly uncomfortable | Uncomfortable | Very uncomfortable

Q7. My perception of the street segment I just walked is:

Unpleasant | Slightly unpleasant | Neither pleasant nor unpleasant | Slightly pleasant | Pleasant

Stop #4:
On 18th street, near the hospital



Q1. What is one or a few words you would use to describe the stretch we have just walked?

Q2. Since the last stop, what percent of the route was covered by shade? Make your best guess.

Q3. We walked past a number of vacant lots since our last checkpoint. Is there anything you would want to see on those lots instead?

Q4: Currently I am:

In full sun | In full shade | In a mix of sun and shade

Q5. At this moment, I am:

Very cold | Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot | Very hot

Q6. My current level of thermal comfort is:

Comfortable | Slightly uncomfortable | Uncomfortable | Very uncomfortable

Q7. My perception of the street segment I just walked is:

Unpleasant | Slightly unpleasant | Neither pleasant nor unpleasant | Slightly pleasant | Pleasant

Stop #5:
19th and Villa

Q1. What is one or a few words you would use to describe the stretch we have just walked?

Q2. Since the last stop, what percent of the route was covered by shade? Make your best guess.

Q3. How do you think the plants contribute to making this neighborhood cooler or warmer in the summer months?

Significantly cooler | Slightly cooler | Neither cooler nor warmer | Slightly warmer | Significantly warmer

Q4. How much do you agree with this statement: Grass is desirable for landscaping in Phoenix

Strongly agree | Agree | Undecided | Disagree | Strongly disagree

Q5: Currently I am:

In full sun | In full shade | In a mix of sun and shade

Q6. At this moment, I am:

Very cold | Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot | Very hot

Q7. My current level of thermal comfort is:

Comfortable | Slightly uncomfortable | Uncomfortable | Very uncomfortable

Q8. My perception of the street segment I just walked is:

Unpleasant | Slightly unpleasant | Neither pleasant nor unpleasant | Slightly pleasant | Pleasant

Stop #6:
Garfield Elementary

Q1. What is one or a few words you would use to describe the stretch we have just walked?

Q2. Since the last stop, what percent of the route was covered by shade? Make your best guess.

Q3. We are looking at the playground at Garfield Elementary School. What do you think about the amount of shade cover available for kids?

The shade amount is excellent | The shade amount is fairly good | The shade amount is not at all good

Q4. If you could change one thing about this playground, what would it be?

Q5: Currently I am:

In full sun | In full shade | In a mix of sun and shade

Q6. At this moment, I am:

Very cold | Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot | Very hot

Q7. My current level of thermal comfort is:

Comfortable | Slightly uncomfortable | Uncomfortable | Very uncomfortable

Q8. My perception of the street segment I just walked is:

Unpleasant | Slightly unpleasant | Neither pleasant nor unpleasant | Slightly pleasant | Pleasant

Stop #7:

Return to Edison Park

Q1. What is one or a few words you would use to describe the stretch we have just walked?

Q2. Since the last stop, what percent of the route was covered by shade? Make your best guess.

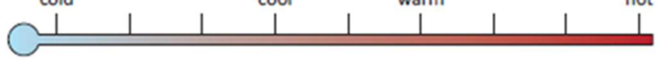
Q3. What is one or few words you would use to describe how you feel right now?

Q4: Currently I am:

In full sun | In full shade | In a mix of sun and shade

Q5. At this moment, I am:

Very cold | Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot | Very hot



Q6. My current level of thermal comfort is:

Comfortable | Slightly uncomfortable | Uncomfortable | Very uncomfortable

Q7. My perception of the street segment I just walked is:

Unpleasant | Slightly unpleasant | Neither pleasant nor unpleasant | Slightly pleasant | Pleasant

Walking interview guiding questions

General experience questions (beginning of the walk):

1. How often and how long do you usually walk?
2. How often and how long do you usually walk?
3. How do you cope with heat while walking?
4. What is important to you when you walk?
5. Would you prefer to walk less under the sun or to walk more in the shade?
6. Landscape specific questions (repeat at every segment):
7. What do you like/dislike about this street?
8. Is it pleasant or unpleasant?
9. Do you feel comfortable/uncomfortable? In what way?
10. What could improve your walking experience?
    a. Probing for design, trees, stores to cool off, cars etc

    Stop #1: On 20th street, north of Van Buren
11. Which side of the street seem more comfortable? Why?
12. What is your opinion about the trees on this street? Grassy courtyards?

    Stop #2: On 16th place, north of Van Buren
13. What do you think about the traffic/noise? To what extent did it influence your experience? In what way?
14. What is your opinion about the bus stops? What differences did you notice? Which one looks more pleasant/comfortable? Why?

    Stop #3: On 18th street, near the hospital

15. What is your opinion about the vacant lots? How do you feel? Comfortable? Secure? Pleasant? Why?

    Stop #4: 19th and Villa

16. What do you think the parking lots? How do you feel? Comfortable? Secure? Pleasant? Why?

    Stop #5: Garfield Elementary

17. What do you think about this playground?
18. Would you want your child to play there? Why

    Stop #6: Return to Edison Park

19. What do you think about the park? Grass? Quality and quantity of trees? Splash pad?
20. What features seems most important for you comfort?
21. Wellbeing questions (end of the walk):
22. Can you say that the built and natural environment affects your wellbeing? In what way?
23. Do you think that walking can improve your lifestyle?
24. Would you be willing to walk more? What would incentivize you to walk more?

APPENDIX C

INTERNAL REVIEW BOARD PERMISSIONS FOR HUMAN SUBJECT TESTING

EXEMPTION GRANTED

Charles Redman
Sustainability, School of
480/965-2923
CHARLES.REDMAN@asu.edu

Dear Charles Redman:

On 5/31/2017 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	The relationship of urban design and microclimate in influencing behavior to mitigate heat exposure on public transit stops in Phoenix Metro Area.
Investigator:	Charles Redman
IRB ID:	STUDY00006309
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• Survey.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Back Translation Form.pdf, Category: Translations; • Survey_Spanish.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • HRP-502a_Consent _SpanishRev1.pdf, Category: Recruitment Materials; • Behavior at transit stops, Category: IRB Protocol; • HRP-502a_Consent_Rev1.pdf, Category: Recruitment Materials;

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) Tests, surveys, interviews, or observation on 5/31/2017.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Yuliya Dzyuban
David Hondula
Yuliya Dzyuban
Charles Redman
Makenna Welsch

ASU Knowledge Enterprise Development

APPROVAL: EXPEDITED REVIEW

David Hondula
Geographical Sciences and Urban Planning, School of
480/965-4794
David.Hondula@asu.edu

Dear David Hondula:

On 9/17/2018 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Edison-Eastlake Nature Conservancy HeatWalk
Investigator:	David Hondula
IRB ID:	STUDY00008752
Category of review:	(6) Voice, video, digital, or image recordings, (4) Noninvasive procedures, (7)(a) Behavioral research
Funding:	Name: Nature Conservancy, Grant Office ID: FP00015019; Name: Piper (Virginia G.) Charitable Trust, Grant Office ID: GR06061
Grant Title:	FP00015019; GR06061;
Grant ID:	FP00015019; GR06061;
Documents Reviewed:	• TNC proposal to Vitalyst Foundation, Category: Sponsor Attachment; • Map of walking routes, Category: Technical materials/diagrams; • TNC Contract for Services 3.22.2018_SS alredits.doc, Category: Sponsor Attachment; • HeatWalk Sample Recruitment Text.pdf, Category: Recruitment Materials; • ConsentForm.Revised.pdf, Category: Consent Form; • HeatWalk IRB protocol Revisedv3.docx, Category: IRB Protocol; • Participant waiver, Category: Other (to reflect anything not captured above); • Walking survey questions, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions);

	• Vanos CITI completion, Category: Non-ASU human subjects training (if taken within last 3 years to grandfather in); • Interview Questions, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions);

The IRB approved the protocol from 9/17/2018 to 9/16/2019 inclusive. Three weeks before 9/16/2019 you are to submit a completed Continuing Review application and required attachments to request continuing approval or closure.

If continuing review approval is not granted before the expiration date of 9/16/2019 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc:

Jennifer Vanos
Yuliya Dzyuban
Patricia Solis