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Abstract

Designing cities for thermal comfort is an important priority in a warming and urbanizing world. As cities continue to break extreme heat records, it is necessary to develop and test new approaches capable of tracking human thermal sensations influenced by microclimate conditions, complex urban geometries, and individual characteristics and thermal perceptions in dynamic settings. Thermal walks are a promising novel research method to address this gap. During a thermal walk in Phoenix, Arizona, USA, we examined the relationships between the built environment, microclimate, and subjective thermal judgments across a downtown city neighborhood slated for redevelopment. Subjects equipped with GPS devices participated in a 1-hour walk on a hot sunny day and recorded their experience in a field guide. Microclimate measurements were simultaneously collected using the mobile human-biometeorological instrument platform MaRTy. Results revealed significant differences in physiological equivalent temperature (PET) between street segments, with streets with higher sky view factor (SVF) and east-west orientation showing a higher PET overall. Furthermore, we showed evidence of thermal alliesthesia, the pleasure resulting from slight changes in microclimate conditions. Participants' sense of pleasure was related to the mean PET of the segment they just walked. Overshoots in pleasure votes occurred at PET transition points; slight increase/decrease in PET resulted in the rise of dis/pleasure respectively. We also showed that estimated percent shade was significantly correlated with SVF, PET, and pleasure, indicating that participants could sense minor changes in microclimate and perceived shade as pleasant. Findings of this study improve the understanding of dynamic thermal comfort in complex urban environments and highlight the value of thermal walks as a robust research method.

1. Introduction

Cities globally are warming due to the changing climate and urbanization (IPCC, 2014). At the same time, planning measures aimed at achieving sustainability goals, mitigating urban heat, and improving health and wellbeing of urban dwellers call for more traversable, safe, physically enticing, and compact city form with enhanced walkability (Beatley, 2000; Berke, 2002; Forsyth, 2015; B. Stone et al., 2010; Wheeler, 2000). Yet, walkability goals can work in the opposite direction as cooling goals. Walkable, compact neighborhoods have high percentages of impervious surfaces (e.g., pavements and buildings), more urban surface area from tall building walls, and mechanical waste heat. These features alter the reflectivity and energy balance of the lower atmosphere creating relatively warmer microclimates called urban heat islands (UHI) (Jenerette et al., 2007; Oke, 1987; B. J. Stone, 2012; B. J. Stone et al., 2007; B. J. Stone & Rodgers, 2001). Traditionally, UHIs are defined as areas of urban climate where surface and air temperatures tend to be warmer than in adjacent undeveloped areas (Oke, 1987), but increasingly researchers are critically reevaluating the use of only simple measures of surface or air temperatures to understand people's thermal experiences of urban climates (Hamstead et al., 2020).

Hamstead and colleagues (2020) suggest thermally resilient communities require more human-centered measures that better represent the complexity of people's thermal experience as a place-based phenomena (Wilhelmi & Hayden, 2010) combining both objective and subjective measures of heat. Planners, designers, and city officials require enhanced people-centered metrics to pursue broader social sustainability and resilience goals such as walkability and livability, which are foundational goals to create socially rich, urban places (Jacobs, 1961).

Achieving these goals without compromising thermal comfort with a warmer built environment requires an understanding of how variations in urban form influence pedestrians in the city.

The practice of heat management is in its infancy in many cities (Hamstead et al., 2020) including the many heat mitigation plans that do not provide adequate justifications for interventions (Dare, 2019). After reviewing 19 North American cities' heat mitigation policies (total of 307 policies), Dare (2019) found that two-thirds of the policies called for blind action without adequate framing of the context (e.g., for public health). Meerow & Newell (2019) suggest building urban resilience to hazards, such as heat, requires asking important questions to frame resilience around a clearer understanding of urban resilience for whom, what, where, when, and why. This framing may require that city officials adjust their assessment methods to better account for how to assess heat as an experiential hazard to inform a greater understanding of that hazard for plans and actions (Hamstead & Coseo, 2019). Many existing policies may only assess simple metrics (e.g., surface and air temperature) to document existing thermal conditions that are then extrapolated into loose proxies for how communities may or may not experience and manage heat as a risk (Dare, 2019; Hamstead & Coseo, 2019; Keith et al., 2019). Dare (2019) also found that many policies to reduce heat favor “visible” strategies (e.g., street tree planting) that may leave out “less visible” but important experiential strategies (e.g., improved transit service, support for utility bills) that could be better accounted for if residents are included in assessments and planning procedures (Guardaro et al., 2020). Such lived thermal comfort data could include assessing pedestrian experiences to better understand the full transit experience from traversing outdoor walkways between home, work, and services and include multiple combinations of travel from walking to taking private vehicles or public transportation (Dzyuban et al., 2021).

From a physiological perspective, an individual's thermal sensation (e.g., cold, hot) depends on the energy balance between the body and the environment. Environmental variables that affect thermal sensations include ambient temperature, radiant temperature, atmospheric moisture, and air movement (Fanger, 1973). Metabolism, skin temperature, blood flow, and sweat production are the main physiological processes that are responsible for energy balance and thermal sensation of the body. These processes depend on the activity and clothing level of the individual (Vanos et al., 2010). Thus, walking individuals will have different thermal sensations than people who do not move. Moreover, pedestrians traverse several microclimate conditions within a short period of time, constantly adapting physiological responses to thermal conditions.

In addition to physiological and behavioral adaptations, there are also psychological, individual, and contextual differences affecting the thermal comfort and sensation of walkers. These include the presence of nature, expectations of what the weather should be like, short and long-term thermal history, time of exposure, ability to choose microclimate conditions, urban design and physical characteristics of space, engagement of multisensory experiences, demographics, culture etc. (Vasilikou & Nikolopoulou, 2020).

Since improved walkability is an objective of many cities worldwide (Shields et al., 2021), exploration of dynamic thermal perceptions of pedestrians moving through complex morphologies is crucial in understanding how to create optimal conditions for walking. In recent years, "thermal walks" have been implemented as a novel methodology to explore the dynamic thermal sensations of individuals moving through streets with various design characteristics (Vasilikou & Nikolopoulou, 2020). Such methodology allows for simultaneous collection of subjective thermal judgments and micro-meteorological data, enabling a more holistic understanding of pedestrian thermal comfort or sensation in natural urban settings. For example, researchers have deployed thermal walks to compare objective and subjective measures of the thermal environment across space and time, (e.g., Chokhachian et al., 2018; Lau et al., 2019; Nakayoshi et al., 2014), understand an additional aspect of a place in relation to the thermal environment (e.g., Dzyuban, 2019; Lau et al., 2019; Ohashi et al., 2018; Vasilikou & Nikolopoulou, 2020; Zhang et al., 2020), and engage stakeholders or public audiences in urban planning and design as it pertains to thermal comfort (e.g., Caverzam Barbosa & Klok, 2020).

The objective of this study is to understand the variations in subjective thermal judgments of pedestrians moving through distinct urban morphologies; the relationships between perceptual and affective thermal sensations, such as thermal sensation vote (TSV), outdoor thermal comfort (OTC), and pleasure scales; and the main drivers of change in these thermal judgments. We also investigated changes in micro-meteorological conditions in relation to urban geometries. To achieve those objectives, we conducted a thermal walk on a hot day in a residential neighborhood in Phoenix, Arizona, USA. This study contributes to the understanding of how variations in urban morphologies and subtle changes in microclimate conditions can trigger variations in subjective thermal judgments. This information can aid in planning decisions for improving pedestrian thermal comfort.

2. Methods

2.1. Study site

Phoenix is one of the hottest cities in the U.S. with more than 110 days of maximum daily temperatures exceeding 38°C (*National Weather Service - NWS Phoenix*, n.d.). The city is located in the Sonoran desert (33.4484° N, 112.0740° W, 331 m above sea level) with a hot arid desert climate (Köppen-Geiger BWh) (Kottek et al., 2006). As a desert city, Phoenix is characterized by horizontal development. Its downtown local climate zones are dominated by open, low-rise designs with patches of large low-rise and bare soil. Tree coverage is low, and vegetation is mostly comprised of shrubs, bushes, and grass (Wang et al., 2018). There is a spatially inequitable distribution of heat in the city, with low-income, minority neighborhoods being hotter and more vulnerable to heat compared to higher income areas. On average, there is a 4°C difference in T_{air} between low and high income communities in Phoenix (Harlan et al., 2006; Jenerette et al., 2015). The thermal walk was conducted in Edison Eastlake, the neighborhood with the highest concentration of public housing in Phoenix and 67% of residents living in poverty. The neighborhood is characterized by degraded infrastructure, a lack of amenities, and poor environmental quality due to a nearby freeway and a superfund site. This predominantly Latino neighborhood was shaped by the history of racial segregation and environmental injustice (Bolin et al., 2005). In an effort to break the poverty trap and improve neighborhood conditions, Edison Eastlake was awarded a Choice Neighborhoods Planning and Action Grant through the U.S. Department of Housing and Urban Development (HUD). The 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. The redevelopment plan was co-created through a city-university-community partnership (Guardaro et al., 2020) that used recognitional, procedural, and distributional environmental justice approaches (Langemeyer & Connolly, 2020) to integrate scientific and community knowledge into planning procedures and documents with a particular focus on heat assessments. The plan also includes improving thermal conditions in the neighborhood since it is currently one of Phoenix's hottest residential areas and most vulnerable to heat. These improvements will include changes in layout and green and grey infrastructure applications (*Edison-Eastlake One Vision Plan*, 2018).

2.2. The thermal walk

The Edison Eastlake neighborhood redevelopment effort provided an exceptional opportunity to track the effect of planning interventions through the implementation of pre- and post-data collecting campaigns. The thermal walk was one of such efforts to establish a baseline of thermal conditions and experiences of the current neighborhood conditions. It is an experimental citizen science project with residents helping to co-create a neighborhood 'heat map'. 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. 14 participants, equipped with GPS devices (QStarz), engaged in a 1-hour walk around the neighborhood and recorded their thermal and visual experiences in a field guide. Participants walked in groups of two to three with slightly staggered times and were escorted by the research team. The "Heat Mappers Walk" event happened on Saturday, September 29, 2018, 16:00–18:00 Local Time (LT), with the walk occurring between 16:18 and 17:18. Phoenix Sky Harbor Airport local air temperature (T_{air}) for the duration of the walk was 37.8°C, with an average wind speed of $3.1 ms^{-1}$, relative humidity (RH) of 17%, and 1/8 to 2/8 cloud cover (*Local Climatological*

Data Station Details: PHOENIX AIRPORT, AZ US, WBAN:23183 | Climate Data Online (CDO) | National Climatic Data Center (NCDC), n.d.) (refer to Supplementary Material (SM), Item 2 for descriptive statistics of meteorological measurements collected over the route). The sunset was at 18:14 that day (*Sunrise and Sunset Times Phoenix, September 2018*, n.d.). Participants received a field guide (SM, Item 1) that included the route map (Figure 1) and survey questions about each walk segment. The 5km walk started in Edison Park and included three residential street segments with various infrastructure characteristics, including minor arterial roads, large areas of vacant land, two hospital parking lots, and a school playground. Seven stops divided the route into street segments. The field guide survey questions 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 their clothing during the walk, their initial thermal sensation vote (TSV), and outdoor thermal comfort (OTC). The third part included stop-specific questions, perceptions of the walked street segment, proposed changes in urban design, and estimated percent of shade per walked segment. TSV and OTC questions were asked in relation to the participant's momentary sensations at the stop (e.g., "At the moment I am:", "My current level of thermal comfort is:"). The perception of pleasure was solicited regarding the previously walked segment (e.g., "My perception of the street segment I just walked is:").

Every walker wore a GPS device to log individual location data. Micrometeorological observations were conducted using the human-biometeorological cart MaRTy (Middel et al., 2021; Middel & Krayenhoff, 2019) . MaRTy measures air temperature, relative humidity, mean radiant temperature, and wind speed and direction as experienced by pedestrians, shaping their thermal sensations. The observations were used to calculate physiological equivalent temperature (PET) and modified physiological equivalent temperature (mPET) for each study participant. PET is defined as the air temperature at which the human body is at heat balance indoors translated to outdoor conditions and is commonly used in thermal comfort studies (Hoppe, 1999). mPET was introduced to address the weaknesses of PET by improving evaluation of the humidity and clothing variability (Chen & Matzarakis, 2018). This project was approved by the Institutional Review Board of Arizona State University (STUDY00008752).

2.3. Data analysis

Georeferenced subject responses were spatially joined with the MaRTy data and mapped using geographic information systems (GIS) software; each participant location point was assigned the closest value from MaRTy. The PET index was calculated from MaRTy observations using the Rayman model (Matzarakis & Rutz, 2010) for each participant. Sky view factor (SVF) for the route was calculated from synthetic fisheye photos (Middel et al., 2017). Stops and segments were manually separated in GIS. Because PET assumes a standard male, 0.9clo, and "standing" metabolic rate, we also calculated the mPET per person. Metabolic rate was based on the median of the non-zero speed data points (representing walking) and time spent standing (~2.5 METs) and converted to a metabolic rate ($1MET=58.15Wm^{-2}$). Metabolic rates were weighted according to time spent doing each activity (walking versus standing) and applied within the mPET model. Body surface area was accounted for based on average male and female dimensions, and age was categorized based on mean of the following ranges: 18–24, 25–44, 45–64, 65+. Clothing type was based on survey responses about what participants were wearing on that day (SM, Item1). For both PET and mPET, non-parametric statistical significance tests (Wilcoxon-Pratt Signed-

Rank) were performed since the data exhibited non-normal trends. Demographic and Likert scale questions from the surveys were analyzed using descriptive statistics and Spearman's Rho correlations to determine significant relationships between subjective thermal judgments and microclimate conditions. TSV and OTC votes were correlated with microclimate data per stop, while pleasure and estimated percent shade was correlated with average microclimate data per segment. To compare changes between the stops across variables with different scales and units, Z-scores were calculated and plotted for subjective sensations, PET, and microclimate variables. All analyses were performed using RStudio (Version 1.3.1056).

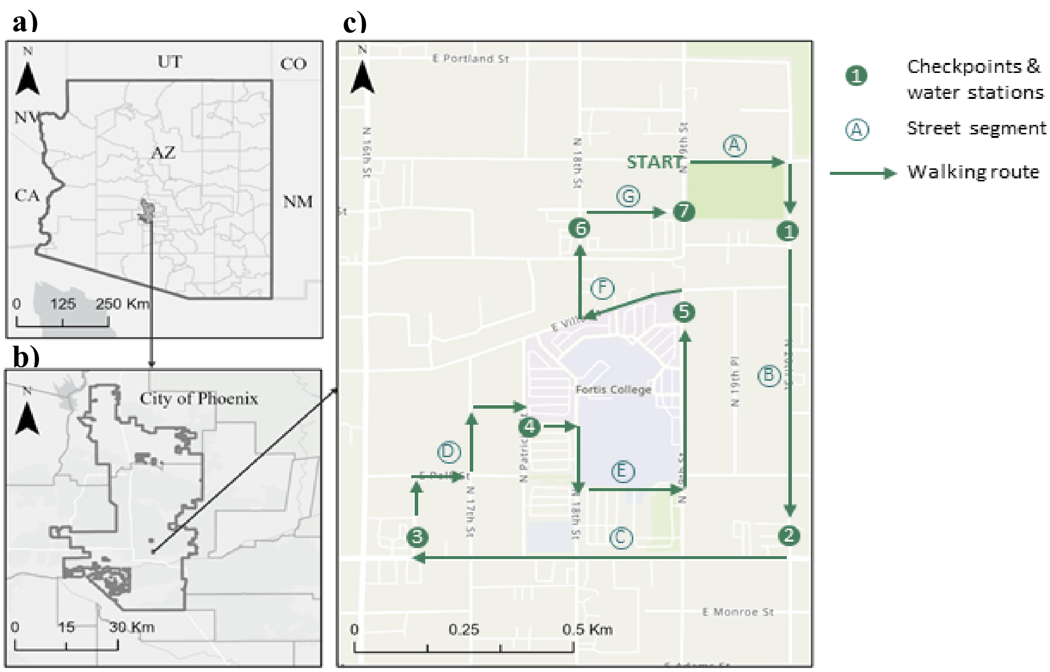

Figure 1. **a)** Geographic location of the City of Phoenix in Arizona, USA; **b)** Geographic location of Edison Eastlake Neighborhood in the City of Phoenix; **c)** Heat Mappers walk route map.

3. Results

3.1. Micro-meteorological measurements and PET in relation to urban morphology

Average T_{air} for the walk was 37.5°C ±0.9°C (SM Item 2). T_{mrt} varied the most out of the meteorological variables with a range of over 30°C and a mean of 54.4°C for the walk. Vapor pressure (VP) and wind speed were low with a mean 11.9hPa and 1.4ms^{-1}, respectively. The average calculated PET and mPET were 47°C (range 15°C) and 44°C (range 20°C), respectively. Note that due to weak relationships of mPET with subjective responses, we focus the remaining results on the PET, and provide discussion for reasoning as to why the mPET did not agree with subjective responses in the given study.

Fluctuations of meteorological variables were evident across the walk (Figure 2). The maximum T_{air} (>38.0°C) was observed in the mid-section of the walk along the east-west arterial road and vacant land segments with little vegetation and shade. T_{air} was the lowest (36.6°C) at 17:08h at segment F impacted by lower afternoon sun and more shade. T_{mrt} was highly variable during the experiment. The highest T_{mrt} (>66°C) was observed at the beginning of the walk in the unshaded area of the park (segment A) and next to vacant land (segment D). The lowest T_{mrt} (34.9°C) was at 17:05h at segment E with afternoon shade from trees and a nearby high-rise hospital building. VP was relatively stable with peaks occurring at the points where T_{air} dipped. Wind conditions also varied, however, remained low overall throughout the walk. PET per participant is mapped in Figure 3. Mean PET was significantly different across the seven street segments (Kruskal-Wallis chi-squared = 1488.8, df = 6, p-value < 0.01). The street segment with the highest mean PET (49.9°C) was next to vacant land (segment D) on the west side of the neighborhood (Figure 4a). The lowest mean PET (43.4°C) was observed at the segment with adjacent two-story residential development (segment F). The maximum PET (54.8°C) was also found at segment D, while the minimum PET (36.5°C) was observed at segment E. Average PET at seven survey stops was also significantly different (Kruskal-Wallis chi-squared = 746.04, df = 6, $p < 0.01$). The highest mean PET was at stop 3 (51.44°C) and the lowest at stop 2 (44.1°C). The maximum PET (54.5°C) was at stop 3, and the minimum (35.3°C) was at stop 7.

Overall, values per stop were clustered closer together as values per stops were taken at one location, while data per segment represents the average for the whole street segment (Figure 4a and 4b). Furthermore, PET of east-west oriented streets was significantly different from PET of the north-south facing streets (Asymptotic Wilcoxon-Pratt Signed-Rank Test, $Z = 34.244$, p-value < 0.01) with east-west streets (mean PET 47.05°C) being significantly hotter than north-south (mean PET 45.2°C).

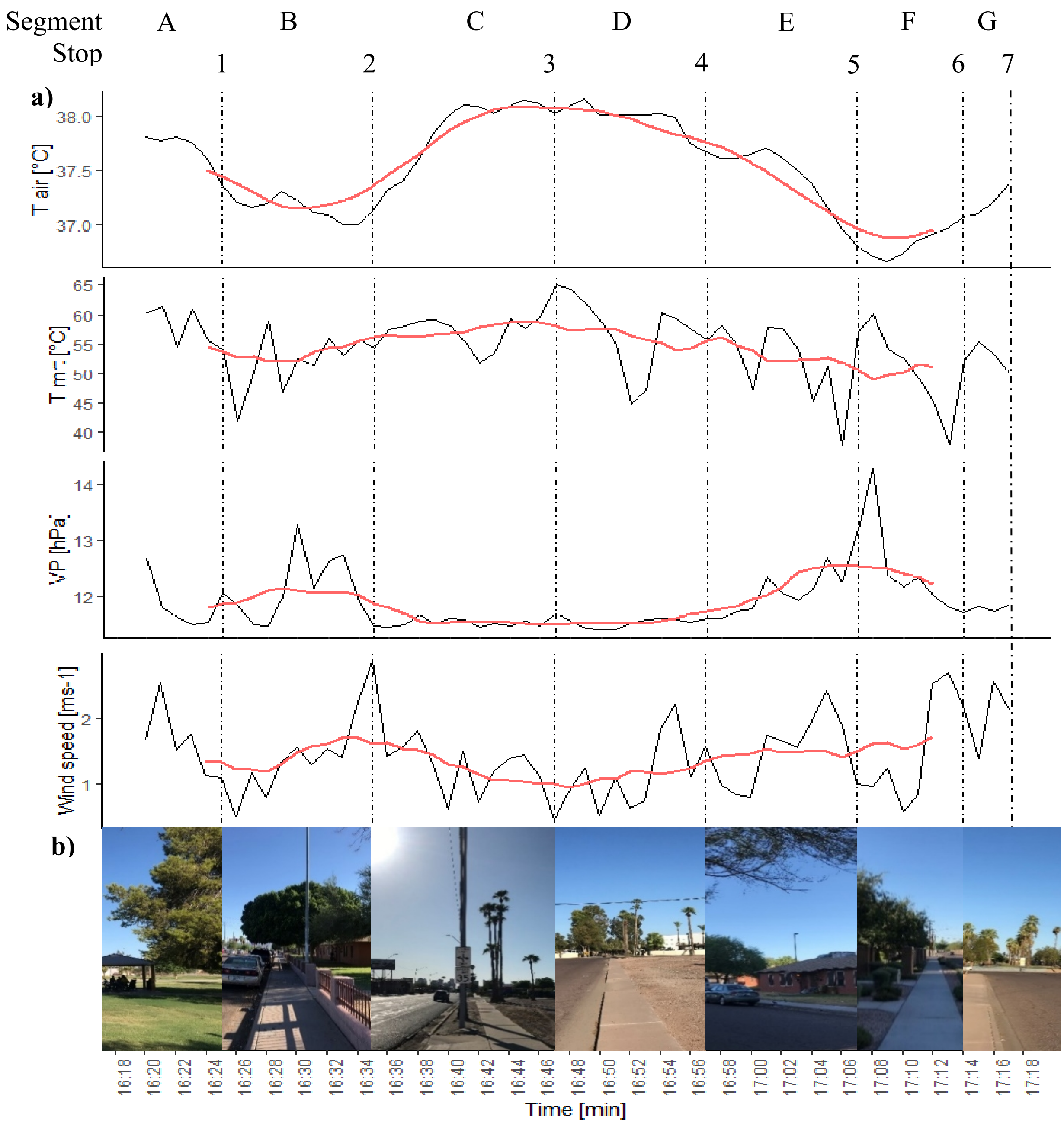

Figure 2. a) Time series of meteorological variables collected during the thermal walk between 16:18 and 17:18 LT, September 29, 2018. Red line is a moving average with k=10; **b)** representative images of respective segments.

Mean SVF per segment varied significantly (Kruskal-Wallis chi-squared = 160.36, df = 6, $p < 0.01$). Mean SVF was generally high with a range of 0.90 to 0.99 (Figure 4a), but minimum segment averages were as low as 0.47. The mean SVF per stop was also significantly different (Kruskal-Wallis chi-squared = 15.87, df = 6, $p = 0.01$), though, none of the pairwise comparisons were. The mean SVF range between stops was 0.95 to 0.99 (Figure 4b). The SVF per segment was significantly correlated with segment number (R^2 =0.33, $p < 0.01$) to all micro-meteorological variables and PET except for wind (T_{air}: R^2 =0.48, $p < 0.01$; T_{mrt}: R^2 =0.41, $p < 0.01$; VP: R^2 = -0.47, $p < 0.01$; PET: R^2 = 0.4, $p < 0.01$). The mean SVF per stop was significantly correlated with all meteorological variables but not with stop numbers (Pearson's cor: T_{air}: R^2 =0.59, $p < 0.01$; T_{mrt}: R^2 =0.39, $p < 0.01$; VP: R^2 = -0.27, $p < 0.01$; PET: R^2 = 0.43, $p < 0.01$, R^2 = v -0.57, $p < 0.01$).

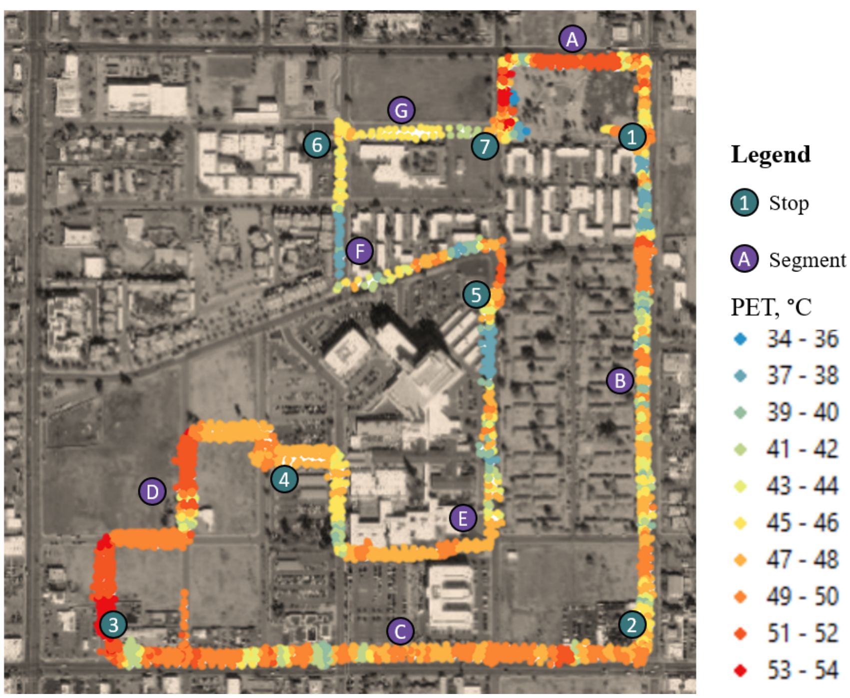

Figure 3. Spatially mapped PET per subject. Each subject's location was matched with the nearest MaRTy data point collected during the thermal walk between 16:18-17:18 LT, September 29, 2018.

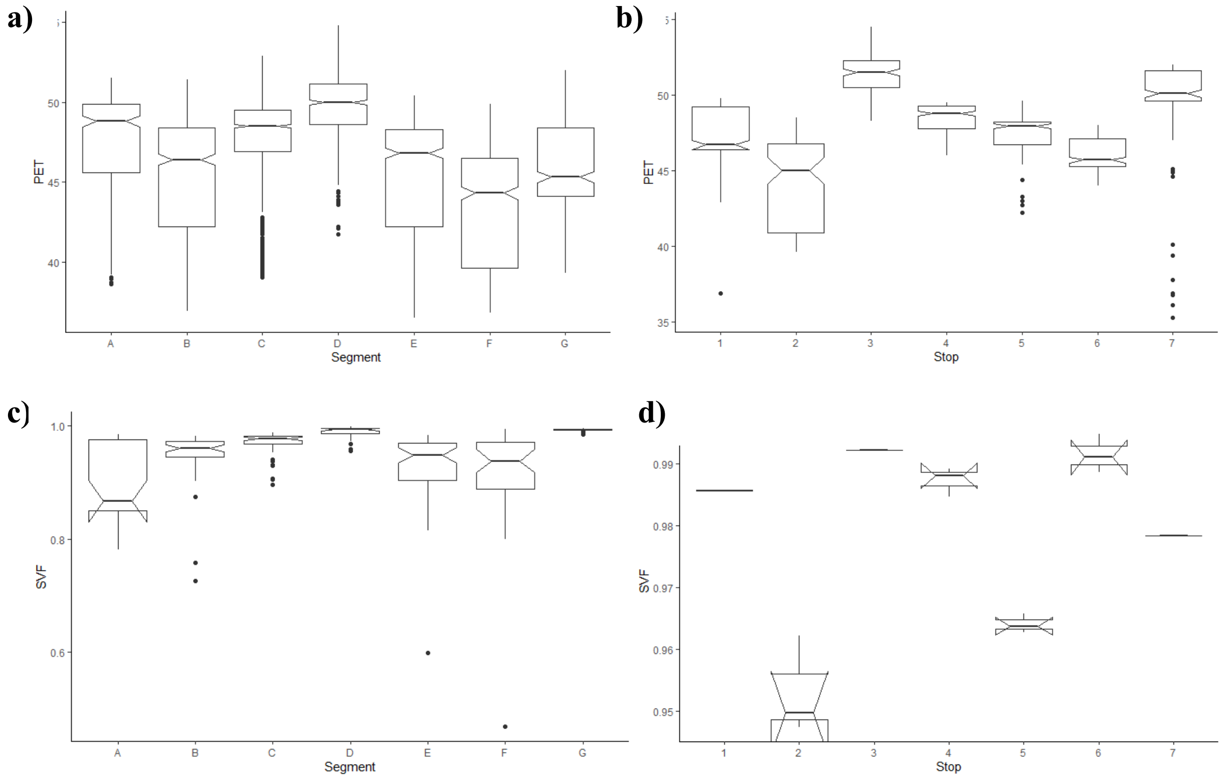

Figure 4. Boxplots of mean differences in PET per **a)** segment, **b)** stop; boxplots of mean differences in SVF per **c)** segment, **d)** stop, as collected during thermal walk between 16:18 and 17:18 LT, September 29, 2018. For each box, the middle line is the median, notches are 95% confidence interal of the median, hinges are interquartile range, whiskers are the 75th percentile of the maximum value, and points are outliers. Horns on SVF figures are the confidence intervals that extend beyond the first or third quartile.

3.2. Survey responses

Eight females and six males participated in the thermal walk. The majority were between 25 and 44 years old (SM Item 3). 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.

3.3. Relationships between microclimate and thermal judgments

Subjective thermal judgments were significantly but weakly correlated with the street segment type, SVF, environmental variables, PET, and mPET (SM Item 4). Among the tested subjective thermal judgments, pleasure had the strongest relationships with VP ($R^2 = 0.39$, $p < 0.01$), T_{mrt} ($R^2 = -0.35$, $p < 0.01$), T_{air} ($R^2 = -0.30$, $p < 0.01$), PET ($R^2 = -0.33$, $p < 0.01$) and mPET ($R^2 = -0.25$, $p < 0.01$).

To understand the sensitivity of thermal judgments to changes in PET, we binned PET into 1°C intervals and calculated mean TSV, OTC, and pleasure vote for each bin. Linear regression did not reveal significant relationships between TSV or OTC and PET. Pleasure was moderately related to average PET per previously walked segment ($R^2 = 0.63$, p = 0.01) (Figure 5).

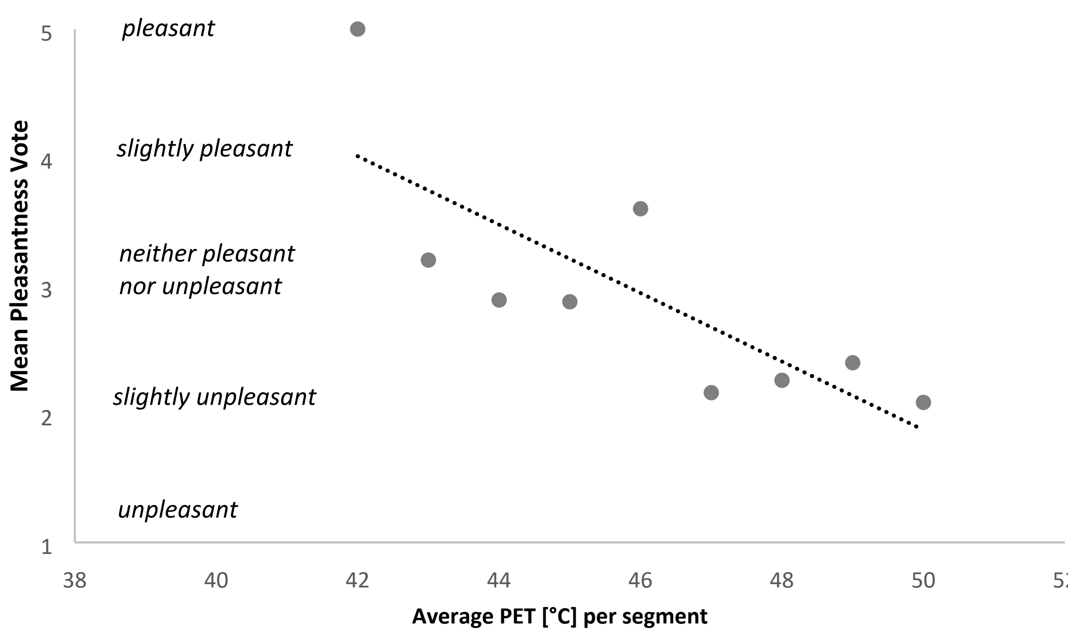

Figure 5. Relationship between mean pleasure votes and binned PET; responses collected during the thermal walk between 16:18 and 17:18 LT, September 29, 2018.

Estimated percent shade was significantly correlated with SVF (R^2 =-0.39, $p < 0.01$), PET (R^2 =-0.58, $p < 0.01$) and pleasure (R^2 =0.39, $p < 0.01$), as well as individual microclimate variables per segment (T_{air}: R^2 =-0.51, $p < 0.01$; T_{mrt}: R^2 =-0.56, $p < 0.01$; VP: R^2 =0.5, $p < 0.01$). SVF was also correlated with pleasure (R^2 =-0.36, $p < 0.01$).

3.4. Changes in thermal judgments

TSV ranged from neutral to very hot at the beginning of the walk with the majority of the participants feeling warm and slightly warm (Figure 6a). Hot and very hot sensation increased in the middle of the walk after passing an unshaded arterial road and vacant land. Improvements in TSV occurred after participants walked along a shaded residential street with large trees and long afternoon shade from buildings, with the majority of the "slightly cool" votes occurring at the end of the walk. The prevailing OTC sensation (Figure 6b) at the beginning of the walk was "slightly uncomfortable". Unlike TSV, OTC gradually decreased with the progression of the walk, with very uncomfortable votes appearing in the second half. Pleasure ranged from "pleasant" to "slightly unpleasant" at the beginning, with most votes in "slightly unpleasant" and "neither pleasant nor unpleasant" (Figure 6c). "Unpleasant" votes occurred at the second stop and were the highest at the 3rd and 4th stops that followed the hottest street segments. Segment E was rated as most pleasant and was followed by a gradual decrease towards the end. TSV was strongly correlated with OTC (R^2 = -0.82, $p < 0.01$) and weakly with pleasure (R^2 = -0.32, $p < 0.01$). OTC was weakly correlated with pleasure (R^2 = -0.33, $p < 0.01$).

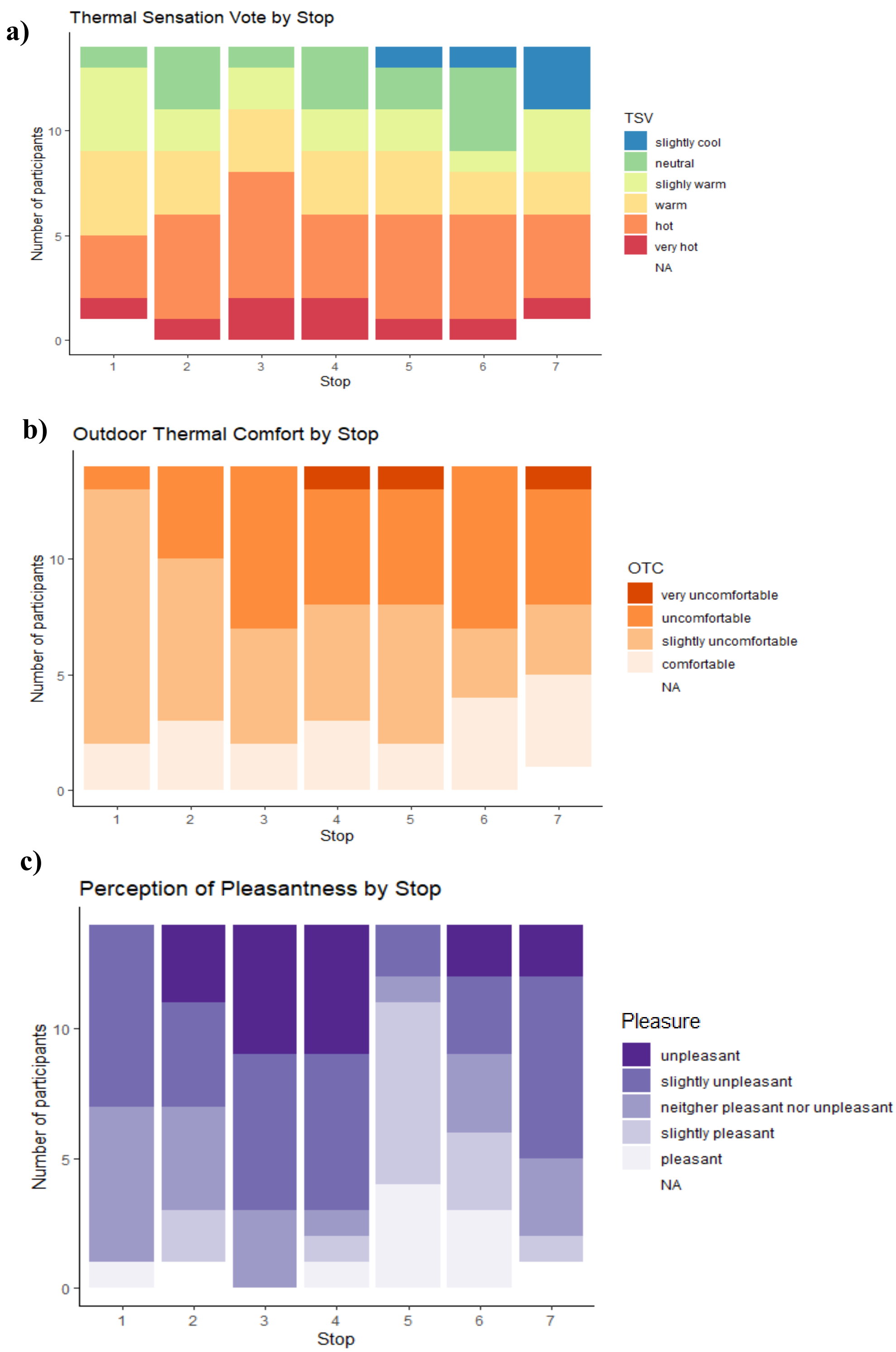

Figure 6. Stacked bar charts showing **a)** TSV, **b)** OTC, and **c)** Pleasure per participant (N=14); responses collected during the thermal walk between 16:18 and 17:18 LT, September 29, 2018.

Furthermore, we calculated z-scores in thermal judgment and micro-meteorological variables for every stop (Figure 7). Z-scores for meteorological variables and PET were calculated from the average value per stop and previous segment. The highest increase in TSV z-scores (1.84) occurred at the 3rd stop that followed the arterial road segment C. TSV improved towards the end of the walk with the decrease in PET and T_{air}. The z-score for OTC was the highest at the beginning of the walk (1.78) and was lowest in the middle (-0.96 at stops 3 and 5). Similar to TSV, the z-score for pleasure was the lowest at stop 3 (-1.05), and the highest at stop 5 (1.84), these changes in pleasure occurred simultaneously with changes in PET, T_{mrt} and T_{air}.

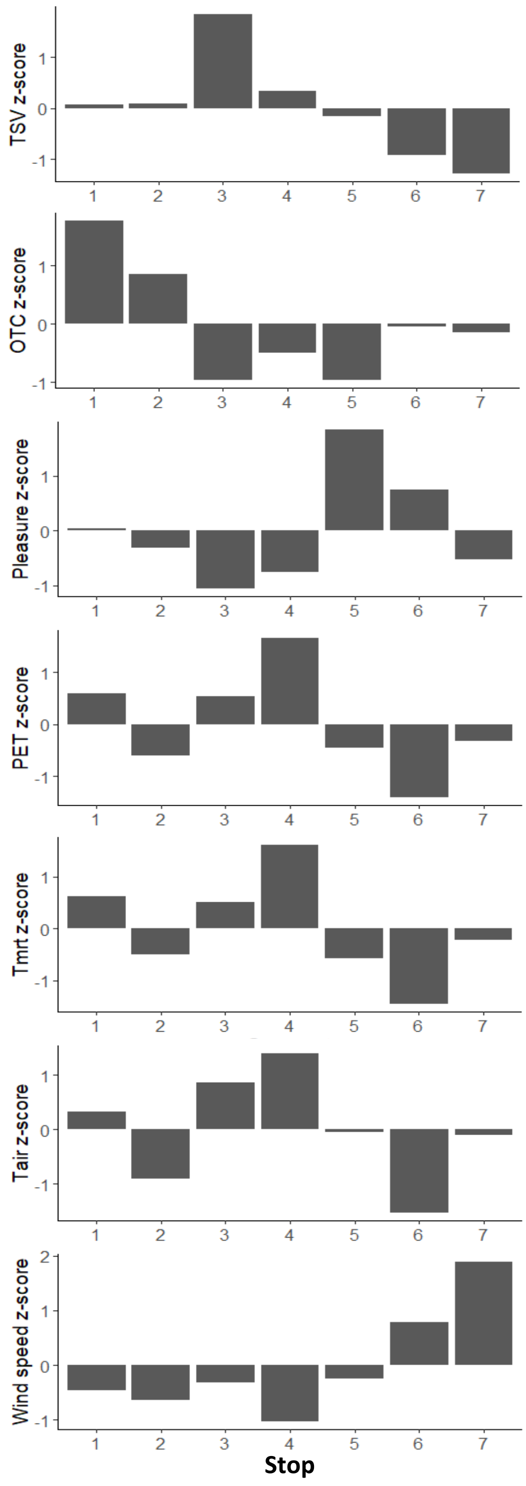

Figure 7. Z-scores for TSV, OTC, pleasure, PET, T_{air}, T_{mrt}, and wind speed. PET, T_{air}, T_{mrt}, and wind speed are averaged per stop and previous segment. Responses and microclimate data collected during the thermal walk between 16:18 and 17:18 LT, September 29, 2018.

4. Discussion

4.1. Effect of street morphology on microclimate

Street morphology and street orientation alter microclimate and thermal comfort mainly through changing shade patterns and wind channeling. SVF, aspect ratio, and street orientation are common metrics to assess street morphology. Studies conducted in hot and dry climates found that streets with high SVF are hotter during the day, with higher differences during the peak hours, and cooler at night (Bourbia & Boucheriba, 2010; Crewe et al., 2016). Furthermore, north-south streets have lower and shorter periods of high PET compared to east-west facing ones (Ali-Toudert & Mayer, 2006). Our results demonstrated the effect of street morphology on microclimate. Segments with the highest mean SVF had the highest mean PET, except for Segment G with the mean SVF of 0.99 which had lower mean PET likely due to the lower sun altitude towards the evening. Segment A had the lowest mean SVF, however, mean PET was high (47.6°C). This is likely due to the east-west street orientation minimizing shade. Segments E and F with lower SVFs of 0.93 and 0.92, respectively, had the lowest PET (45.19 °C and 43.43°C). Moreover, we showed that street orientation had a significant effect on PET, with east-west oriented streets having a significantly higher PET compared to north-south.

4.2. Subjective thermal judgments and sensitivity to microclimate

TSV and OTC were not significantly correlated with PET in this study. This is in alignment with other studies showing low sensitivity to small ranges in PET (Banerjee et al., 2020), especially when temperatures are above the acceptable range (Dzyuban et al., 2021). A study in the same climate determined that participants reported a year-round neutral temperature of 28.6°C with an acceptable thermal range 19.1-38.1°C (Middel et al., 2016). The mean PET (46.0°C) in the current study is much above the acceptable range. Moreover, another study showed weak relationships between MTSV and UTCI and PET for walking individuals, which is attributed to non-steady state conditions of pedestrians in motion (Yuchun Zhang et al., 2020). The only subjective perception significantly related to microclimate and urban morphology was perception of pleasure, which we argue can be explained by the framework of thermal alliesthesia.

4.3. Thermal alliesthesia

A feeling of (dis)pleasure resulting from an environmental stimulus is defined as thermal alliesthesia. Positive thermal alliesthesia occurs when the applied stimulus is in direction towards restoring thermal equilibrium of the body (Cabanac, 1979). This phenomenon is useful in describing dynamic thermal sensations in non-steady environments (Shooshtarian, 2019). Alliesthesia is strongest at the point of change and disappears when the body reaches thermal equilibrium. Thus, feeling of pleasure can only occur after conditions that cause thermal discomfort. Thermal alliesthesia occurs due to the firing of dynamic thermoreceptors in the body and is evident as an "overshoot" in thermal sensations. Thermal overshoots are stronger for larger environmental differences and are usually more apparent when conditions change from warmer towards cooler (De Dear, 2010). In an outdoor experiment where subjects were exposed to alternate sun and shade conditions and local cooling at different metabolic rates, there was a strong linear relationship in increased pleasure from a cooling effect when subjects previously felt hot and vice versa. A moderate quadratic relationship was present when subjects were within a thermoneutral zone (cooler or warmer than preferred) with only mild alliesthesia (Liu et al., 2020). The present study has clearly demonstrated the effect of thermal alliesthesia. We found a moderate linear relationship between mean pleasure votes and PET. A thermal overshoot is evident with the increase in the z-score for pleasure by 2.59 at stop 5 with a simultaneous, but smaller decrease in the PET z-score by 2.11. These changes in PET were mainly caused by reduction of the T_{mrt} z-score by 2.9 and increase in the wind speed z-score by 0.78. This is in line with another study showing that after T_{mrt}, wind speed becomes an important factor in affecting thermal sensations. (Yuchun Zhang et al., 2020). Notably, the largest changes in subjective thermal judgments occurred at the point of change in PET and not at the lowest value of PET. For instance, the largest spike in TSV and drop in OTC and pleasure occurred at stop 3 after PET started to increase but did not peak; and the largest increase in pleasure occurred at stop 5 following the decrease in PET but not at its minimal value (Figure 8). Moreover, SVF was significantly correlated with estimated percent shade and pleasure, showing that subjects were sensitive to changes in SVF, and they associated shadier areas with pleasure.

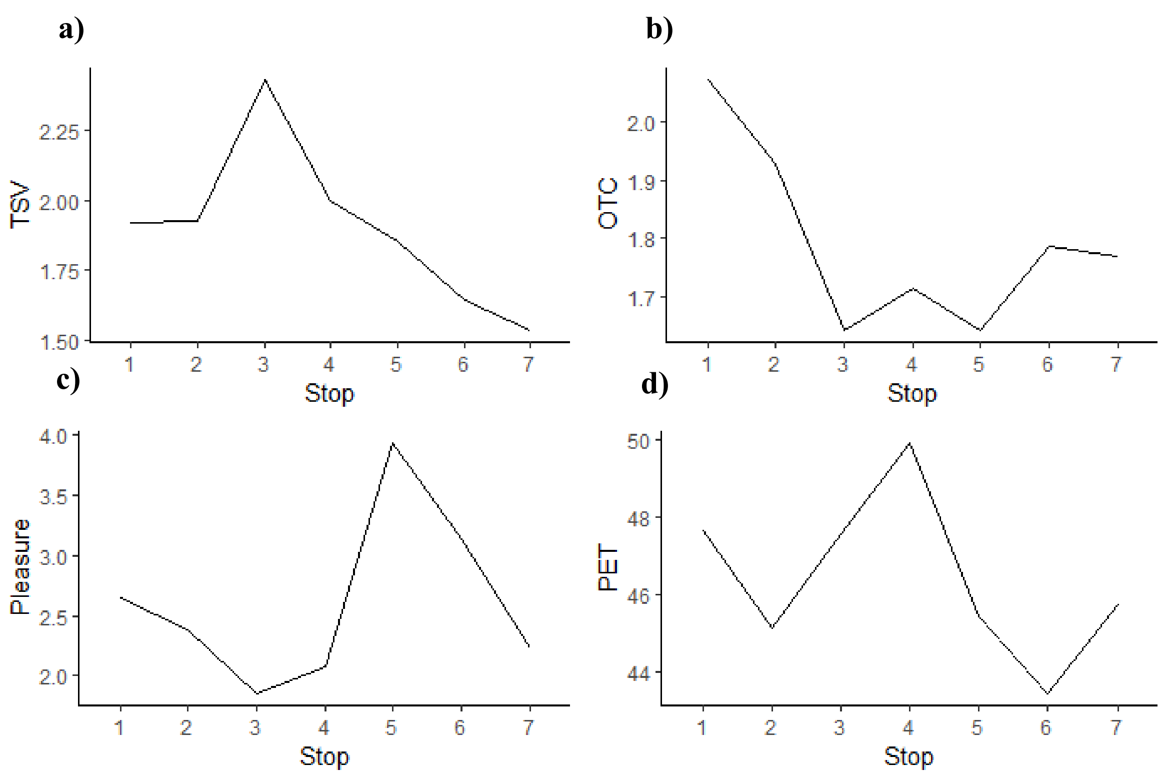

Figure 8. Series of mean **a)** TSV, **b)** OTC, **c)** Pleasure, and **d)** PET per stop collected during the thermal walk between 16:18 and 17:18 LT, September 29, 2018.

4.4. Perceptual vs hedonic scale

Many studies on thermal comfort define thermal neutrality as an optimal state and thermal comfort as a middle range of values on the thermal sensation scale. However, concepts such as thermal sensation, thermal comfort, and thermal pleasure are distinct and have complex relationships. While TSV indicates the strength of thermal stimulus it does not provide information on the state of comfort of the individual (De Dear, 2011). In steady-state conditions, these concepts are closely related; however, in non-steady state environments these relationships are not straightforward, because sensations such as thermal preference and thermal pleasure become more prominent (Yufeng Zhang & Zhao, 2008). The current study shows the complexity between TSV, OTC and pleasure. TSV and OTC were strongly correlated, but both were weakly correlated with pleasure. TSV and OTC judgments were instantaneous regarding to the current state of the individuals. Since conditions at stops had little variance, we did not identify significant relationships with microclimate. At the same time, questions about pleasure were in regards to the previously walked segment, demonstrating the effect of alliesthesia and thermal history on subjects' responses. We recommend researchers continue to use dynamic methods such as thermal walks to better capture the complexity of the human thermal experience through space and time and to better inform design and planning interventions.

4.5. Implications for research and practice

Warming trends in cities and summer temperature extremes require a change of how we view thermal comfort and design cities. Achieving neutral sensations in such conditions is unlikely, and the feasibility towards that should be questioned. Methodologies such as thermal walks can better capture people's lived experience of heat and show the evidence of the effect of design on achieving pleasant sensations. This should be utilized in design by exploring the alliesthesial potential of different urban design attributes. In addition, thermal comfort is not a universal state and varies based on the socio-cultural differences, type of activity, and time of exposure, thus, it is important to explore outdoor thermal comfort for different population groups and among diverse routes and walk durations. To understand better how thermal overshoots and alliesthesia can be utilized in design, research should shift towards exploring dynamic conditions and thermal judgments in the context of those versus single-point measurements in particular locations. Thermal walks meet these aims, and we look forward to the expansion and adoption of this methodology moving forward.

5. 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 sensation, especially in dynamic situations. This study has addressed both; however, it has several limitations that should be considered and overcome in future work. Diurnal changes in temperature 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 participants. In our case, it was important to prioritize participants' safety as noon temperatures could expose them to potentially dangerous conditions. Another limitation is that PET model assumes a constant clothing insulation of 0.9 clo which is too high for hot conditions, as well as it uses a constant metabolic rate of 80W added to basal metabolism, which is a low activity level. Furthermore, PET is calculated for an 'average' male and female with standardized age, height, and weight. Studies showed that performance of the models between TSV and PET improved when actual metabolism level was added to the equation; however, when we added metabolism, general age, clothing, and sex into the PET to calculate mPET, it did not improve the relationship with TSV as hypothesized. This finding may be due to using non-dynamic metabolic rate across the walk, rough body/age/clothing approximations, and extremely low humidity. Collecting heart rate data to accurately calculate metabolism could potentially improve our results; thus, future work should include such measurements in a dynamic way to match with the microclimate data, as well as collect body height, weight, clothing, and exact age. Finally, differences in the units and scales across variables allows for different interpretations of "small" and "large" changes between them. We chose to use z-scores to make more standardized comparisons between variables, but the z-scores are dependent on the range of values collected during the experiment rather than any absolute scale. We encourage the development of more consistent methods to compare meteorological variables and subjective thermal comfort indicators.

6. Conclusions

Warming trends in cities and summer temperature extremes require a change of how we view thermal comfort and design cities. We have demonstrated the effect of street morphology on PET: overall, open street segments with minimal landscaping and high SVF had the highest PET, as well as east-west oriented streets were hotter than north-south facing with over 6°C in mean PET difference between segments and over 18°C difference in PET between the coolest and the hottest areas. Furthermore, this study demonstrated the evidence of thermal alliesthesia through spikes in pleasure votes triggered by smaller reductions in PET. Notably, the largest differences in subjective thermal judgments tended to occur at the point of change in microclimate and not at the lowest/highest values per se. Low sensitivity of TSV and OTC votes to small PET variations and differences in TSV, OTC, and pleasure responses showed the importance to collect both perceptual and affective thermal judgments for a holistic understanding of pedestrian thermal comfort. This study demonstrates the value of collecting people-centric metrics such as dynamic thermal comfort and provides a framework for exploring alliesthesial potential of various urban design attributes in non-steady state conditions that can be utilized to inform design practices and ensure livability in hot climates.

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Data to this article can be found online at https://portal.edirepository.org/nis/mapbrowse?scope=edi&identifier=1042

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