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Evidence of alliesthesia during a neighborhood thermal walk in a hot and dry city

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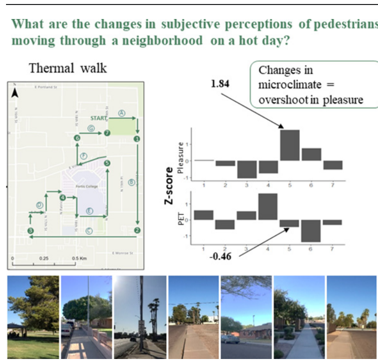
HIGHLIGHTS

- Pedestrian thermal comfort varied across different urban streets on a hot day.
- PET and mPET were significantly different.
- Alliesthesia (feeling of dis/pleasure) was evident.
- Even small changes in microclimate and shade were pleasurable for participants.
- Thermal walk method revealed how urban design can influence thermal perception.

GRAPHICAL ABSTRACT



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ABSTRACT

Designing cities for thermal comfort is an important priority in a warming and urbanizing world. As temperatures in 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 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 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 physiologically equivalent temperature (PET) and modified physiologically equivalent temperature (mPET) and between street segments with more than 18 °C (25 °C mPET) between the maximum and minimum values. Wider range of mPET values reflected the inclusion of individual level data into the model. Streets with higher sky view factor (SVF) and east-west orientation showed a higher PET and mPET 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, with

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linear regression explaining over 60% of the variability. We also showed that estimated percent shade was significantly correlated with SVF, PET, mPET, and pleasure, indicating that participants could sense minor changes in microclimate and perceived shade as pleasant. Although generalization of results is limited by a low sample size, 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; Stone, 2012; Stone et al., 2007; Stone and Rodgers, 2001). Traditionally, UHIs are defined as areas of urban climate where surface and air temperatures tend to be warmer than in adjacent rural 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 et al. (2020) suggest that thermally resilient communities require more human-centered measures that better represent the complexity of people's thermal experience as a place-based phenomena (Wilhelmi and 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 and Newell (2019) suggest that 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 and 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 and 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., 2022).

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 wind speed (Fanger, 1972). 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 and ambient factors such as extreme weather conditions (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. (Knez et al., 2009; W. Liu et al., 2016; Nikolopoulou et al., 2001; Ouameur and Potvin, 2007; Potvin, 2000; Shooshtarian and Ridley, 2017; Vasilikou and Nikolopoulou, 2020; Yahia and Johansson, 2013).

Moreover, a framework of thermal alliesthesia, a feeling of dis/pleasure, is useful in describing dynamic thermal sensations in non-steady environments (Shooshtarian, 2019). Positive thermal alliesthesia occurs when the applied stimulus is in direction towards restoring thermal equilibrium of the body (Cabanac, 1979). 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).

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 and 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 and 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 and 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 micrometeorological 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 and 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, 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 (ASU) Urban Climate Research Center and Knowledge Exchange for Resilience. Participant and volunteer recruitment was completed via public advertising by the Nature Conservancy, Museum of Walking, and ASU. Advertising channels included organizational websites, social media, and in-person announcements at relevant meetings convened by each organization. All participants were required to have health insurance. Fourteen participants, equipped with GPS devices (QStarz), engaged in a 1-h walk around the neighborhood and recorded their thermal and visual experiences in a field guide. Participants drove to the site in private vehicles and spent 30 min at the park before the actual walk took place, adjusting themselves to the outdoor conditions. Participants were aware of the basic heat protection measures and wore light clothes, hats, and sunscreen. Drinking water was offered to them at every stop. 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, with the walk occurring approximately between 16:00 and 17:00 Local Time (LT). 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, n.d.). Participants received a field guide (SM, Item 1) that included the route map (Fig. 1) and survey questions about each walk segment. The 5 km 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. Fisheye images representing conditions at stops and average conditions per segment are presented in Fig. 2. 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. MaRTy measures air temperature, relative humidity, shortwave and longwave radiation flux densities, and wind speed as experienced by pedestrians, shaping their thermal sensations. Measurements were taken at pedestrian height (1.5 m for T_{air} and relative humidity, 1.7 m for wind speed, 1.1 m to 1.3 m for long- and shortwave radiation) (Middel and Krayenhoff, 2019). Mean radiant temperature T_{mrt} was calculated from collected shortwave (*Ki*) and longwave (*Li*) radiation with angular factors (*Wi*) for a standing reference person (Höppe, 1992; VDI, 1998):

$$T_{mrt} = \sqrt[4]{\frac{\Sigma_{i=1}^{6} W_i(a_k K_i + a_l L_i)}{a_l \cdot \sigma}} - 273.15\ K$$

where $a_k = 0.70$ and $a_l = 0.97$ are the absorption coefficients for shortwave and longwave radiant flux densities, σ is the Stefan-Boltzmann constant, $W_i = 0.06$ for the up and down facing sensors, and $W_i = 0.22$ for the sensors pointing in each cardinal direction.

The observations were used to calculate physiologically equivalent temperature (PET) and modified physiologically 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 (Mayer and

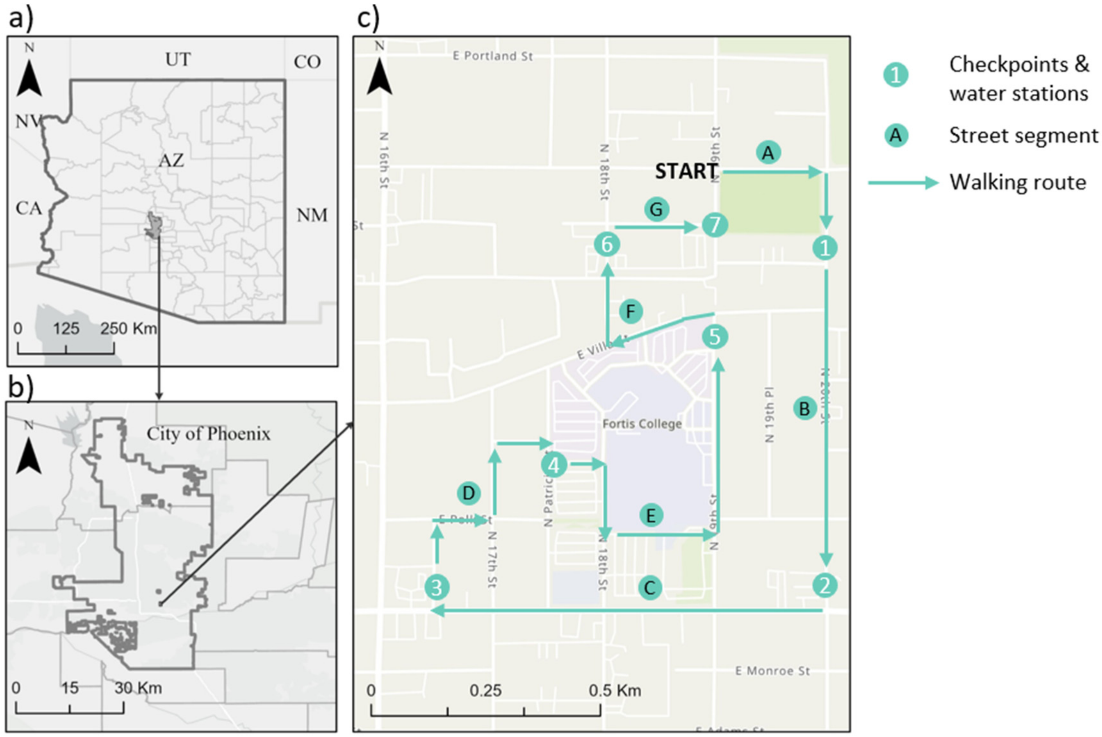

Fig. 1. a) Geographic location of the City of Phoenix in Arizona, USA; b) Geographic location of Edison Eastlake Neighborhood in the City of Phoenix; c) Thermal walk route map.

Höppe, 1987). mPET was introduced to address the weaknesses of PET by improving evaluation of the humidity and clothing variability (Chen and 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 and mPET indices were calculated from MaRTy observations using the RayMan model (Matzarakis et al., 2007) for each participant. Sky view factor (SVF) for the route was calculated using fisheye photos generated from Google Street View panoramic images (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. Subjective thermal judgments were separately tested for correlations with average meteorological values per stop, previously walked segment, and combined average per stop and previous segment. To compare changes between the stops across variables with different scales and units, *Z*-scores were calculated and plotted for subjective sensations, PET, mPET, and microclimate variables. All analyses were performed using RStudio (Version 1.3.1056).

3. Results

3.1. Micro-meteorological measurements, PET, and mPET 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 11.9 hPa and 1.4 ms^{-1}, respectively.

Fluctuations of meteorological variables were evident across the walk (Fig. 3). 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 17:08 LT 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 17:05 LT 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 Fig. 4. In hot and dry conditions PET is most sensitive to T_{air} and T_{mrt} (Middel and Krayenhoff, 2019). We observed a similar trend with T_{air} explaining over 80% of variability in PET (R^2 = 0.83, $p < 0.01$), while T_{mrt} explained 96% ($p < 0.01$). The difference of T_{mrt} and T_{air} (T_{mrt} - T_{air}) explained 95% ($p < 0.01$) showing that in our study radiative component was most influential on PET. On the other hand, mPET was less sensitive to T_{air} and T_{mrt}. T_{air} explained 50% of the difference in mPET ($p < 0.01$), and T_{mrt} and T_{air}-T_{mrt} explained 56% of the variation ($p < 0.01$).

Mean PET (46.6 °C) was significantly higher than mPET (44.5 °C) (Asymptotic Wilcoxon-Pratt Signed-Rank Test: Z = 53.6, $p < 0.01$). Furthermore, both mean PET and mPET were significantly different across

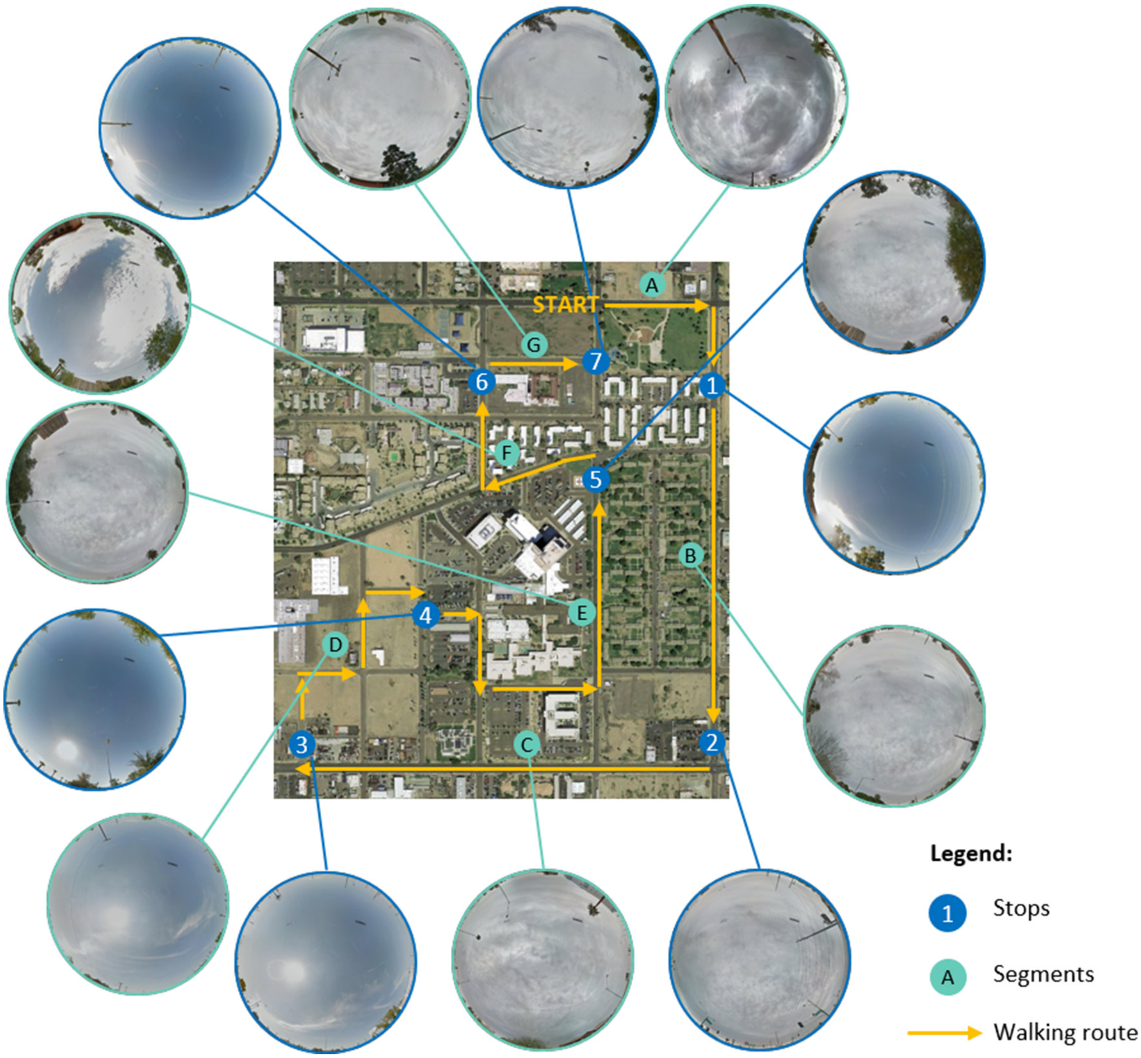

Fig. 2. Fisheye photos for stops (numbers) and segments (letters) of the thermal walk in Edison Eastlake Neighborhood.

the seven street segments (PET: Kruskal-Wallis chi-squared = 1488.8, df = 6, $p < 0.01$; mPET: Kruskal-Wallis chi-squared = 1361.4, df = 6, $p < 0.01$). The street segment with the highest mean PET and mPET (49.9 °C and 47 °C respectively) was next to vacant land (segment D) on the west side of the neighborhood (Fig. 5a and c). The lowest mean PET and mPET (43.5 °C and 42 °C respectively) was observed at the segment with adjacent two-story residential development (segment F). The maximum PET and mPET (54.8 °C and 61.4 °C respectively) was also found at segment D, while the minimum PET and mPET (36.5 °C for both) was observed at segment E. Average PET and mPET at seven survey stops was also significantly different (PET: Kruskal-Wallis chi-squared = 746.04, df = 6, $p < 0.01$; mPET: Kruskal-Wallis chi-squared = 699.26, df = 6, $p < 0.01$). The highest mean PET and mPET was at stop 3 (51.4 °C and 47.1 °C respectively) and the lowest at stop 2 (PET 44.1 °C and mPET 41.8 °C). The maximum PET and mPET (54.5 °C and 50.1 °C respectively) was at stop 3, and the minimum (PET 35.3 °C and mPET 36.4 °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 (Fig. 5a, c and b, d). Furthermore, PET and mPET of east-west oriented streets was significantly different from PET and mPET of the north-south facing streets (Asymptotic Wilcoxon-Pratt Signed-Rank Test, Z = 34.24, $p < 0.01$) with east-west streets (mean PET 47.1 °C and mean mPET 41.2 °C) being significantly hotter than north-south (mean PET 45.2 °C and mean mPET 39.9 °C).

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 (Fig. 5e), 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 (Fig. 5f). The SVF per segment was significantly correlated with segment number ($R^2 = 0.05$, $p < 0.01$) to all micro-meteorological variables, PET, and mPET (T_{air}: $R^2 = 0.31$, $p < 0.01$; T_{mrt}: $R^2 = 0.3$, $p < 0.01$; VP: $R^2 = -0.32$, $p < 0.01$; V: $R^2 = -0.09$, $p < 0.01$; PET: $R^2 = 0.29$, $p < 0.01$; mPET: $R^2 = 0.13$, $p < 0.01$) (SM Item 4). The mean SVF per stop was also significantly correlated with stop number ($R^2 = 0.23$, $p < 0.01$), all meteorological variables, PET, and mPET (T_{air}: $R^2 = 0.57$, $p < 0.01$; T_{mrt}: $R^2 = 0.39$, $p < 0.01$; VP: $R^2 = -0.2$, $p < 0.01$; V: $R^2 = -0.57$, $p < 0.01$; PET: $R^2 = 0.47$, $p < 0.01$; mPET: $R^2 = 0.47$, $p < 0.01$) (SM Item 5).

3.2. Relationships between microclimate and thermal judgments

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.

Among the tested subjective thermal judgments, pleasure had the strongest relationships with average values per stop and previous segment VP

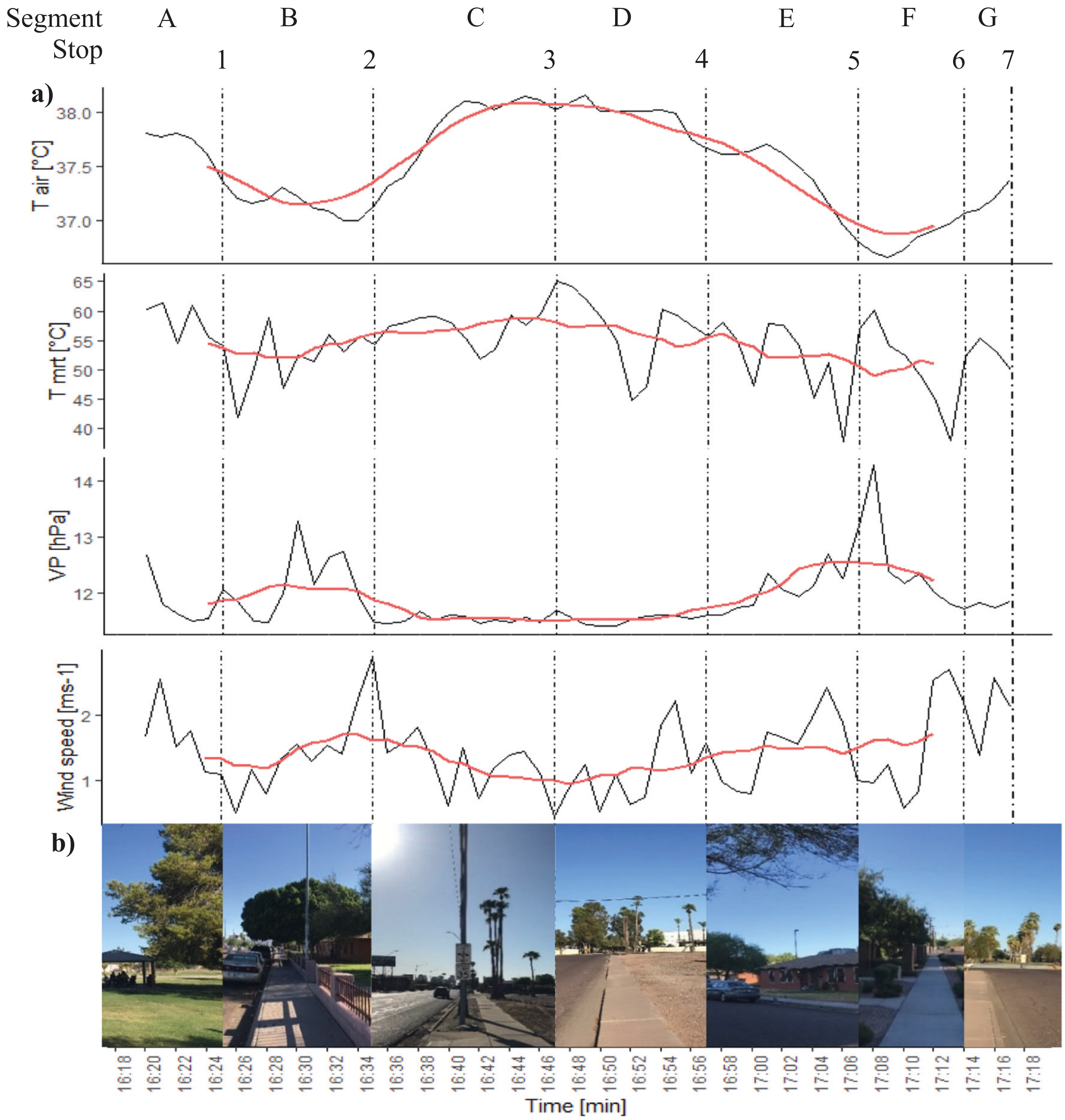

Fig. 3. a) Time series of meteorological variables collected during MaRTy transect between 16:18 and 17:18 LT, September 29, 2018. Red line is a moving average with k = 10; b) representative images of respective segments.

(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, $p < 0.01$). TSV had the strongest relationship with mPET (R^2 = 0.21, $p < 0.01$), VP (R^2 = −0.13, $p < 0.01$) and Tair (R^2 = 0.11, $p < 0.01$) (SM Item 6). OTC had the strongest relationship with wind (R^2 = −0.14, $p < 0.01$) and mPET (R^2 = −0.1, $p < 0.01$). TSV and OTC were slightly stronger correlated with average mPET values per stop (R^2 = 0.23, $p < 0.01$ and R^2 = −0.19, $p < 0.01$ respectively) but no significant correlations were identified with PET or other meteorological variables (SM Item 5).

To understand the sensitivity of thermal judgments to changes in PET and mPET, we binned PET and mPET 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. Pleasure was moderately related to average PET per previously walked segment (R^2 = 0.63, p = 0.01) (Fig. 6), no significant relationship was found for mPET.

Estimated percent shade was significantly correlated with average values per previously walked segment for SVF (R^2 = −0.21, $p < 0.01$), PET (R^2 = −0.62, $p < 0.01$), mPET (R^2 = −0.48, $p < 0.01$) and pleasure (R^2 = 0.38, $p < 0.01$), as well as individual microclimate variables per segment (T_{air}: R^2 = −0.53, $p < 0.01$; T_{mrt}: R^2 = −0.58, $p < 0.01$; VP: R^2 = 0.57, $p < 0.01$). SVF was also correlated with pleasure (R^2 = −0.21, $p < 0.01$) (SM Item 4).

3.3. Changes in thermal judgments

TSV ranged from neutral to very hot at the beginning of the walk with most of the participants feeling warm and slightly warm. 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 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". "Unpleasant" votes occurred at the

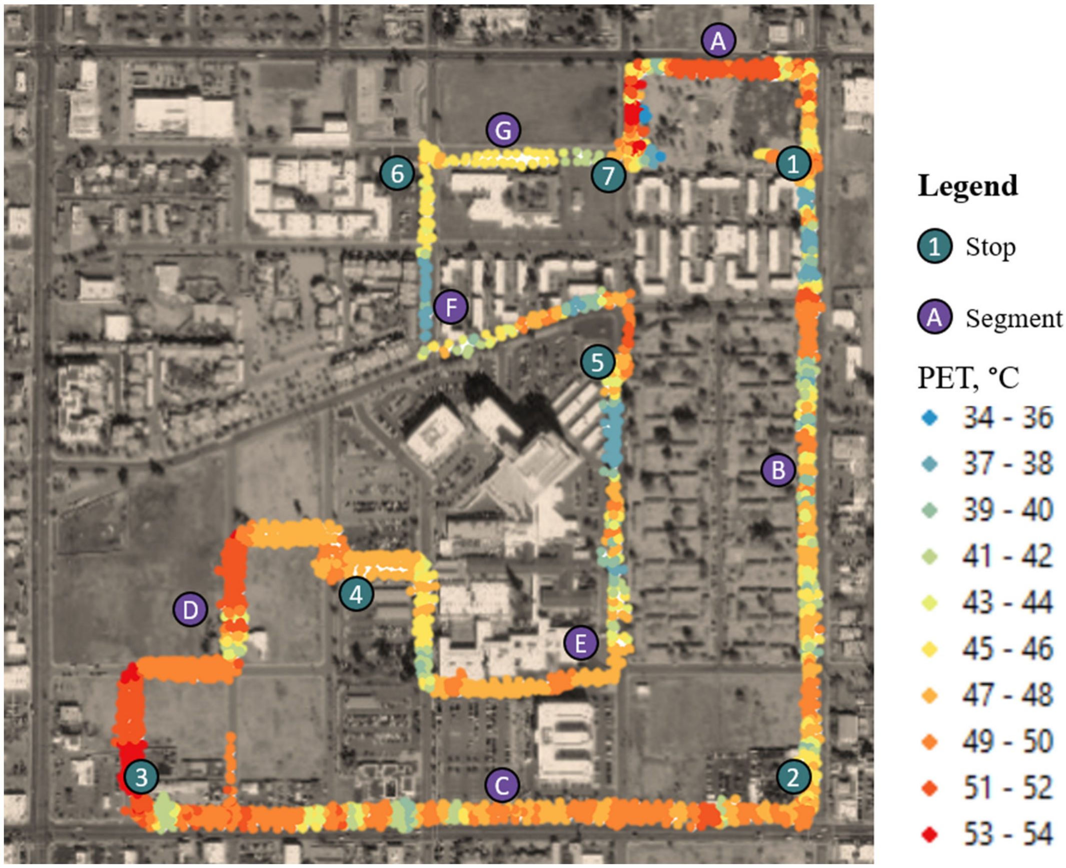

Fig. 4. Spatially mapped PET per subject. Each subject's location was matched with the nearest MaRTy data point collected during the thermal walk between 16:00–17:00 LT, September 29, 2018.

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 ($R^2 = -0.33$, $p < 0.01$).

Furthermore, we calculated z-scores in thermal judgment and micrometeorological variables for every stop (Fig. 7). *Z*-scores for meteorological variables, PET, and mPET 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, mPET, 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, mPET, T_{mrt} and T_{air}.

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 and 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 and Mayer, 2006). Our results demonstrated the effect of street morphology on microclimate. Segments with the highest mean SVF had the highest mean PET and mPET, except for Segment G with the mean SVF of 0.99 which had lower mean PET and mPET likely due to the lower sun altitude towards the evening. Segment A had the lowest mean SVF, however, mean PET and mPET was high (47.6 °C and 46.4 °C respectively). 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 (45.2 °C and 43.4 °C) and mPET (43.6 °C and 42.1 °C). Moreover, we showed that street orientation had a significant effect on PET and mPET, with east-west oriented streets having a significantly higher PET and mPET compared to north-south.

4.2. Subjective thermal judgments and sensitivity to microclimate

TSV and OTC per stop were significantly but weakly correlated with mPET in our study. This indicates a slighter better sensitivity of mPET to momentary thermal sensations due to better adjustment for evaporation, metabolism, and clothing. Overall average PET was significantly higher than mPET, which can be explained by the low atmospheric moisture. However, mPET values were distributed within a wider ranger (18.5 °C compared to 8.6 °C for PET), which can be attributed to inclusion of gender, age, clothing, and metabolic differences in the mPET model. TSV and OTC per stop were not significantly correlated with PET in this study. This is in alignment with other studies showing differential importance of specific microclimate parameters such as wind speed and thermal radiation as well as variables related to clothing, culture, expectations, seasonality, and thermal history (Liu et al., 2016; Yahia and Johansson, 2013). Our findings also align with studies demonstrating low sensitivity to small ranges in PET (Banerjee et al., 2020), especially when temperatures are above the acceptable range (Dzyuban et al., 2022). A study in the same climate

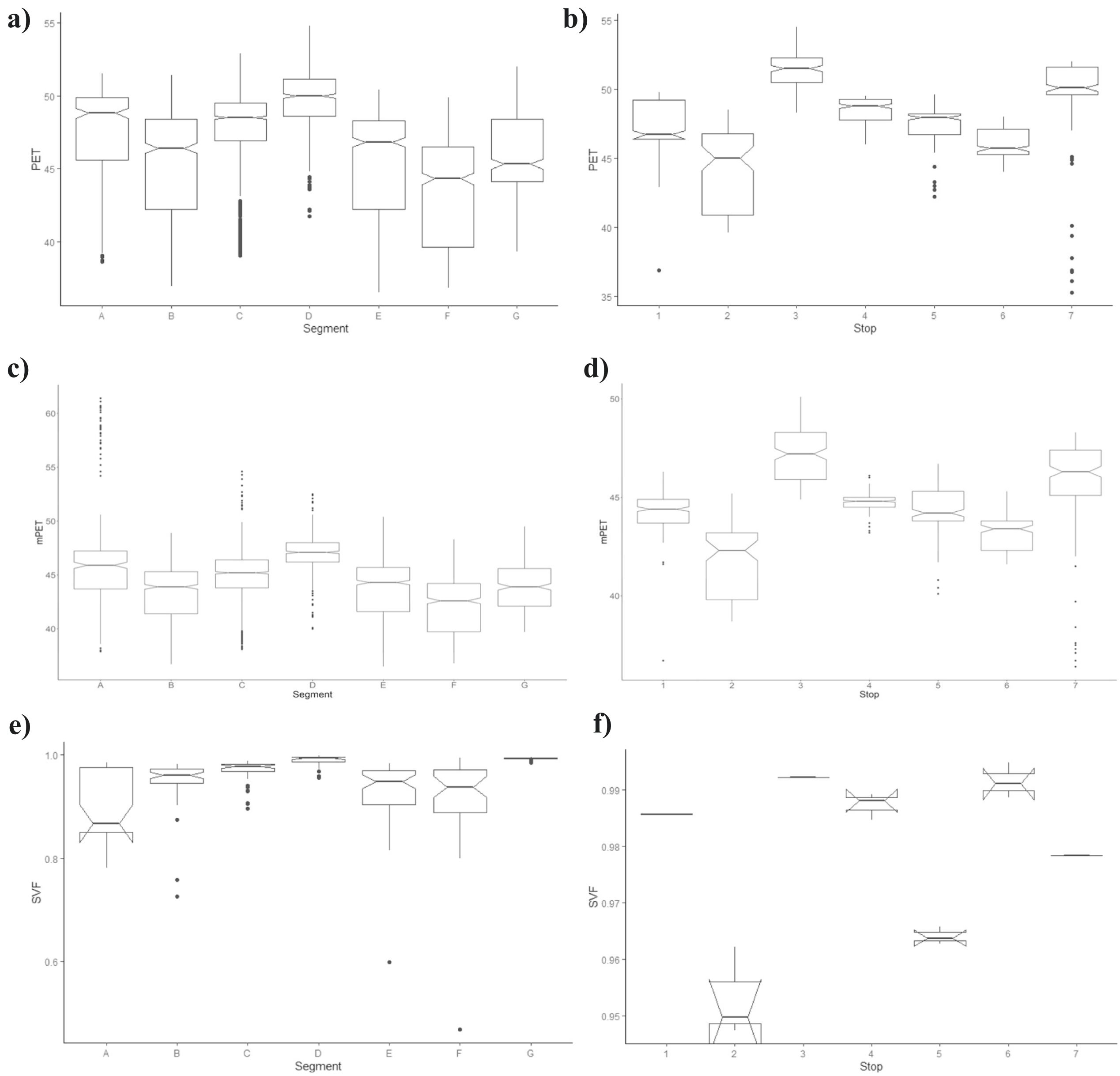

Fig. 5. Boxplots of mean differences in PET per a) segment, b) stop, and mPET per c) segment, d) stop; boxplots of mean differences in SVF per e) segment, f) stop, as collected during thermal walk between 16:00 and 17:00 LT, September 29, 2018. For each box, the middle line is the median, notches are 95% confidence interval 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.

determined that participants reported a year-round neutral PET temperature of 28.6 °C with an acceptable thermal range 19.1–38.1 °C (Middel et al., 2016). Other studies in a city with similar climate, Köppen-Geiger BWh (Kottek et al., 2006), Cairo, Egypt, showed neutral PET range of 21.6 °C–30.1 °C and 24.3 °C–29.5 °C (Potchter et al., 2018) and acceptable comfort PET range of 23 °C–32 °C (Elnabawi et al., 2016). A study in neighborhoods of Sidi Okba in Algeria, Köppen-Geiger BWh, (Kottek et al., 2006), showed acceptable comfort range between 24 °C and 32 °C (Mouada et al., 2019). The mean PET (46 °C) in the current study is much above the neutral and acceptable ranges discussed above. 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). Linear regression model showed that the only subjective perception significantly related to PET (but not mPET) was perception of pleasure, which we argue can be explained by the framework of thermal alliesthesia.

4.3. Thermal alliesthesia

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 (Fig. 8). Moreover, SVF

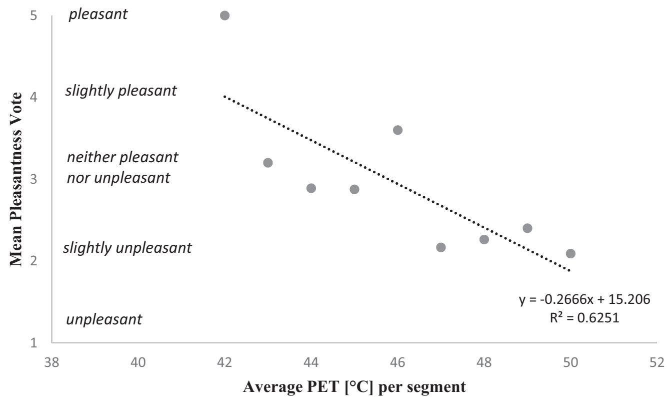

Fig. 6. Relationship between mean pleasure votes and binned PET; responses collected during the thermal walk between 16:00 and 17:00 LT, September 29, 2018.

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. We believe that the linear model showed significant relationships between pleasure and PET but not mPET because radiative component had the strongest influence on the perception of pleasure in this study. In the results section we showed that radiative component had a stronger influence on PET than on mPET ($R^2 = 0.96, p < 0.01$ vs $R^2 = 0.56, p < 0.01$)

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 and 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 between TSV and OTC per stop and microclimate, but there were slight effects of wind, T_{air}, and VP from previously walked segment. On the other hand, we showed the relationships between TSV, OTC and mean mPET per stop, showing that mPET better reflects instantaneous sensations. Furthermore, questions about pleasure in regard to the previously walked segment demonstrated 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. A study of various urban configurations in hot and dry Tolga, Algeria, showed considerable increase in heat stress over the 30-year period (Matallah et al., 2021). Hot and dry climate poses unique challenges to outdoor thermal comfort design strategies and need to be reflected in urban planning policies (Matallah et al., 2021). Some strategies that are identified as beneficial for improved walkability in temperate climates, should be applied judiciously in desert conditions (Negev et al., 2020). Study in Damascus,

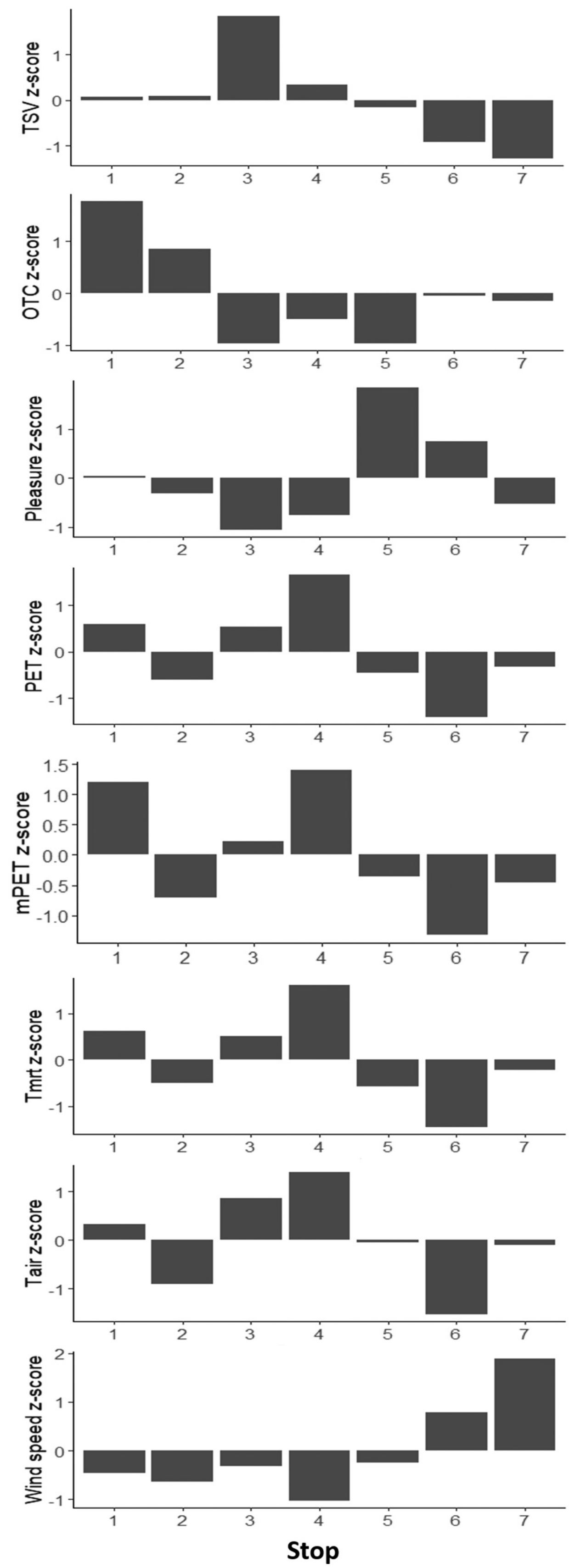

Fig. 7. *Z*-scores for TSV, OTC, pleasure, PET, mPET, T_{air}, T_{mrt}, and wind speed. PET, mPET, T_{air}, T_{mrt}, and wind speed are averaged per stop and previous segment. Responses and microclimate data collected during the thermal walk between 16:00 and 17:00 LT, September 29, 2018.

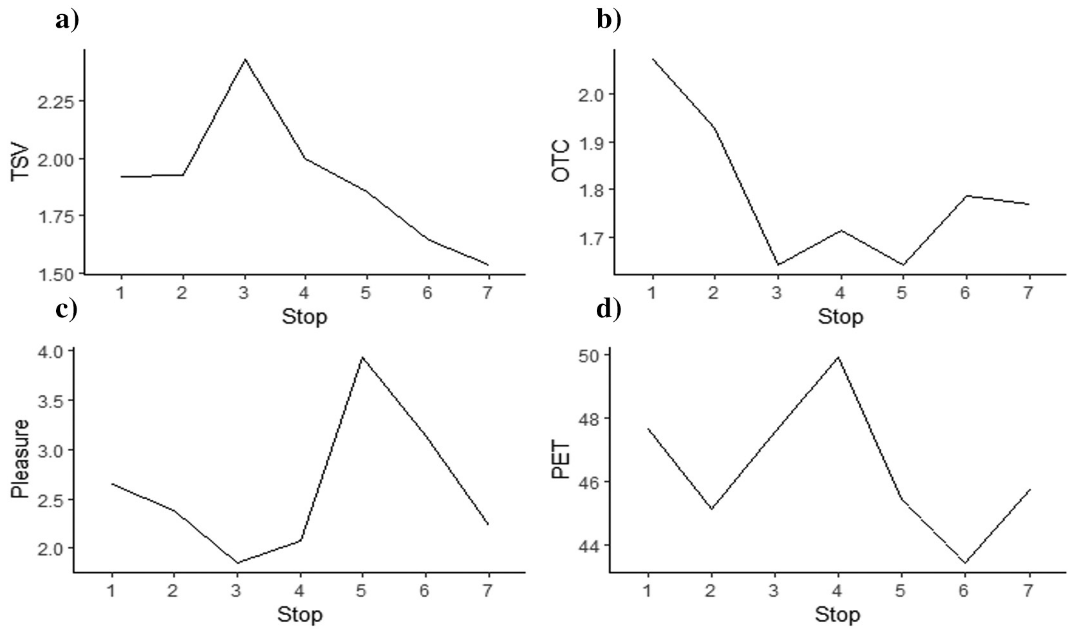

Fig. 8. Series of mean a) TSV, b) OTC, c) Pleasure, and d) PET per stop collected during the thermal walk between 16:00 and 17:00 LT, September 29, 2018.

Syria, showed that urban morphology, vegetation, and street orientation have a strong influence on microclimate. Combining trees and shading devices is an effective measure in reducing PET (Yahia and Johansson, 2014). Ample shade should be provided along pedestrian routes with short walking time to and from public transit stops. Vegetation needs to be prioritized in areas next to pedestrian traffic and combined with artificial shade to conserve water (Negev et al., 2020). Spaces between buildings are also important to consider in urban planning (Yahia and Johansson, 2014).

Achieving neutral sensations in hot and dry 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. Relatedly, in order to effectively engage study participants, we accepted a limited sample size of 14 individuals. While this number is in range of similar heat walk studies (e.g., Chokhachian et al., 2018; Lau et al., 2019), it limits findings to that of uncovering evidence rather than observing a generalizable phenomenon. 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 80 W 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. When we added metabolism, general age, clothing, and sex to calculate mPET, it only slightly improved correlations with TSV and OTC. 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 and mPET: overall, open street segments with minimal landscaping and high SVF had the highest PET and mPET, as well as east-west oriented streets were hotter than north-south. Mean PET was significantly higher than mPET by more than 2 °C. However, mPET had more than twice the range of values compared to PET (18.5 °C vs 8.6 °C respectively). We showed that mPET had lower sensitivity to weather due to an inclusion of the differences in metabolic rates, and individual characteristics of the participants. As a result, TSV and OTC had weak but significant correlations with mPET but not PET. However, pleasure was more strongly correlated with PET. Since T_{mrt} explained over 95% of the difference in PET, we hypothesized that radiation component had the strongest effect on pleasure. 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. 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.

CRediT author statement

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J. K. Vanos: data curation, investigation, review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.155294.

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