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Hot and bothered: Exploring the effect of heat on pedestrian route choice behavior and accessibility

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ABSTRACT

Although many cities are incentivizing non-auto modes of transportation in response to the climate crisis, their sustainable mobility transition efforts are being challenged by the rising intensity and frequency of heatwaves. Pedestrians are exposed to high levels of heat stress on hot days, which may reduce their willingness to walk. It is thus important to understand how heat affects pedestrian behavior and accessibility, so that climate mitigation strategies can be better targeted to support walking as a mode of transport but also as a first-/last-mile connection to public transit. In this study, we used a dataset of pedestrian trips undertaken during the summer of 2014 in Boston, MA. Along with several route attributes (such as length, turns, sidewalk width, amenities, Normalized Difference Vegetation Index, and Sky View Factor), we also included a measure of heat stress (Universal Thermal Climate Index - UTCI) to explain pedestrian route choice behavior. Using path-size logistic regression models, we found evidence to suggest that heat stress has a considerable and statistically significant effect on the perceived walking distance. We also found that the effect was non-uniform and possibly exponential. Additionally, we illustrated the extent to which heat stress can reduce pedestrian accessibility to important destinations (such as public transit). This reduction was significant on a typical summer day, with an even sharper reduction on the hottest summer day. Non-White residents were observed to have lower accessibility levels compared to all pedestrians, likely because of disparities in urban heat exposure. Our findings highlight the importance of incorporating heat exposure into transportation planning and urban design frameworks, especially with an equity lens to address unequal consequences.

1. Introduction

To be(lieve) or not to be(lieve), that is a moot question when it comes to climate change. We are experiencing extreme weather events such as heatwaves, droughts, hurricanes, and floods at historically rapid and unpredictable rates, with some communities bearing more of the brunt than others. As the global population continues to grow and urban agglomeration accelerates, these hazards will only become more pronounced and imminent. To address these concerns meaningfully, we will need to pivot away from our auto-dependent approach to mobility that has been and continues to be a significant contributor to greenhouse gas (GHG) emissions in particular and climate change at large (Basu, Ferreira, 2021a; Newman & Kenworthy, 1999). It has become necessary to promote and incentivize a modal shift away from single-occupancy private vehicles to mass transportation and active travel modes such as walking, cycling, and rolling. After a century of prioritizing the automobile, many cities are now recognizing the importance of centering pedestrians in their transportation policies and planning practices. A growing focus on enhancing urban walkability to create more walkable cities has been catalyzed by efforts to improve urban sustainability (Berger et al., 2014), public health (Grasser et al., 2013), and economic competitiveness (Glaeser, 2012).

The walkability of a city is affected by its thermal environment, whereby the outdoor thermal comfort for pedestrians plays a key role in determining the quality of urban life. Many cities are experiencing unprecedented climate impacts related to rising temperatures, which can vary spatially within a city due to the heterogeneous nature of urban environments (and intensity of urban heat islands). The increasing number of hot days and frequent occurrences of heatwaves can cause a serious threat to human life. Trips that entail physical exertion outdoors,

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such as walking and biking trips, will increase people's overall exposure to potentially dangerous urban microclimates. Unfortunately, most urban walking spaces are planned by functionality, with little consideration of thermal comfort. If transportation planners and urban designers exclude climate-conscious considerations in their practices, the potential threat to public health and pedestrian comfort is likely to be exacerbated as pedestrians are comparatively more exposed to extreme weather conditions. Socially disadvantaged groups (low-income individuals and zero-vehicle households) and vulnerable groups (elderly individuals and children) are likely to be disproportionately affected by heat exposure during walking (Karner et al., 2015). Therefore, understanding pedestrian behavioral adaptation to urban thermal environments is critically important not just from a sustainability perspective, but from an equity perspective as well.

Understanding the effect of urban morphology on microclimate and thermal comfort, and subsequently on pedestrian behavior, is challenging. Although health and thermal comfort researchers have explored the effect of urban morphology, research on the link to pedestrian behavior is still relatively nascent. Previous studies present an incomplete and fragmented picture of the impact of weather (especially heat) on travel behavior, which makes effective planning for climate change a tall task (Böcker, Dijst, et al., 2013a). In this study, we attempt to bridge the literatures on outdoor thermal comfort and travel behavior by exploring how heat affects pedestrian decision-making in choosing between different routes to the same destination.

We used actual pedestrian trajectories (chosen routes) from a large-scale dataset of pedestrian activity in Boston, MA to explore how heat affects pedestrian route choice. We selected pedestrian trips made during the summer and constructed choice sets with up to three feasible alternatives for each chosen route. We computed several route attributes — route length, number of turns, sidewalk width, amenities passed along the route, Sky View Factor (SVF), and Normalized Difference Vegetation Index (NDVI) — which were used as independent variables to explain pedestrian route choice. We also included the Universal Thermal Climate Index (UTCI) as a measure of thermal comfort along each route, which was computed using historical data at the time of the trip actually being taken. Using path-size logistic regression models, we tested whether heat stress (as measured by UTCI) was able to explain pedestrian route choice during the summer in Boston.

Similar to prior literature, we found that heat stress (UTCI) does not influence all trips. It seems to matter only for trips where there are alternative routes with diverse UTCI values compared to the chosen route. Furthermore, we detected a non-linear effect of UTCI on pedestrians' perceived distance. While the average effect of 1 °C increase in UTCI (beyond the comfort threshold of 26 °C) is 80.8 meters, separating the effect by heat stress categories (e.g., 26 °C to 29 °C, 29 °C to 32 °C, etc.) leads to varied effects across these categories that likely resemble an exponential increase. We also translated these results into assessments of transit accessibility for pedestrians. Our findings indicate that not accounting for heat stress can lead to considerable over-estimation of the sizes of public transit catchment areas. Not only does heat stress shrink pedestrians' accessibility to transit (and other important destinations) on a typical summer day, the shrinkage effect is significantly larger on hotter days. This study uniquely, and possibly for the first time at this spatio-temporal scale, demonstrates how heat stress plays a significant role in pedestrian route choice behavior and accessibility. Our research can help inform infrastructure investment decisions and public policies for the promotion of healthy, equitable, and walkable communities.

The remainder of this paper is structured as follows. In the following section, we summarize previous studies that have explored how weather affects travel behavior. We also focus on pedestrian route choice studies in particular and identify several gaps in these literatures that we address in this study. We then introduce readers to the study area (Boston, MA), discuss our data sources and data generation processes, and provide an overview of the quantitative methods used for empirical analyses. We report model estimation results in the next section, along with a discussion of our findings in light of the existing literature. Finally, we conclude by summarizing the key takeaways from this paper and suggest a few promising avenues for future research.

2. Literature review

Although weather is known to affect travel behavior, the effects are quite nuanced. Not only does the type of weather (e.g., heat vs. precipitation) matter, changes in travel behavior in response to weather conditions are highlight dependent on trip purpose (Cools et al., 2010). Understandably, weather plays a larger role in affecting recreational and leisure trips compared to utilitarian trips such as commuting (Liu et al., 2015; Thomas et al., 2013). Adverse weather conditions, such as extreme heat, have been found to result in a switch from open-air to sheltered transport modes, while also decreasing the number of visits and reducing the distance traveled to outdoor destinations (Böcker et al., 2013a,b; Creemers et al., 2015; Wu & Liao, 2020). In addition to the choice of mode, departure times, travel times, and routes can also be influenced by weather conditions (Böcker et al., 2016).

Active mode users, such as pedestrians and bicyclists, are most sensitive to the weather, whereby good weather conditions have been found to induce more positive emotions during travel (Böcker et al., 2016). The impact of weather on active modes of transportation is significant enough to deserve attention at different levels, including research, data collection, and planning (Saneinejad et al., 2012). Air temperature, sunlight, and precipitation have all been found to be significantly associated with pedestrian activity (de Montigny et al., 2012). Walking trips tend to be relatively shorter in hotter temperatures (Bergström & Magnusson, 2003). Other studies have also detected a negative effect of high temperatures combined with high humidity on active transportation modes (Aultman-Hall et al., 2009; Gebhart & Noland, 2014). On adverse weather days, pedestrians may engage in various adaptation strategies — (a) switch to a different travel mode, (b) change the destination such that the trip length is shorter, (c) change the route such that the trip is more comfortable, (d) change the departure time to when the weather is more pleasant, or (e) forgo the trip. Studies exploring the interdependencies between weather and travel behavior have mostly focused on mode choice and trip generation. Very little attention has been given to the effect of weather on route choice behavior, which is an important adaptation strategy for pedestrians during extremely hot days.

Pedestrian route choice is known to be influenced by three major categories of factors — (a) pedestrian socio-demographics, (b) the built environment, and (c) trip characteristics (Basu et al., 2022; Brown et al., 2007; Götschi et al., 2017; Guo & Ferreira Jr., 2008; Guo & Loo, 2013; Le et al., 2018; Papadimitriou et al., 2009). Age, gender, ethnicity, occupation, income, and the presence of companions have been found to affect pedestrian route choice. Key built environment features include sidewalk characteristics, street crossing facilities, amenities along the sidewalk, route infrastructure (street signs and streetlights), land use along the route, condition of the buildings, pedestrian density, residential and non-residential density, safety, security, quality of the walking environment, and topography. Trip attributes such as the distance or length of the trip, traffic volume, walking time, and the posted speed limit are also associated with pedestrian route choice. While these factors have been extensively studied over the last couple of decades, only a few studies have hinted at how pedestrians adapt their route choice preferences during hot weather by seeking shade. On extremely hot days, pedestrians have been found to seek shaded places when standing at traffic signals (Watanabe & Ishii, 2016). Interviews of pedestrians have revealed that they are aware of the dangers of solar radiation and often prioritize shade over other factors in their route choice as a defensive mechanism to avoid solar radiation (Azegami et al., 2023). Researchers have also recently estimated that a walk in the shade feels 14 % shorter than the same walk in the sun, with shadows cast by buildings found to play a larger role than trees (Melnikov et al., 2022). Some of these findings have been extended to create a pedestrian routing tool to support pedestrians in navigating urban heat (Neset et al., 2022).

Pedestrian thermal comfort goes beyond mere shade. Several studies have noted the effect of street design on mitigating the adverse effects of urban heat islands and improving pedestrian thermal comfort (Jamei et al., 2016; Jamei & Rajagopalan, 2019). Street-level vegetation has been found to be particularly effective in improving thermal comfort and urban resilience to anthropogenic climate change (Jia & Wang, 2021; Piselli et al., 2018). It is worth noting that any type of infrastructure or intervention which causes the greatest reduction in air temperature does not necessarily lead to the biggest improvement in thermal comfort and walkability. This is because thermal comfort is a multi-faceted construct that takes several weather conditions into account. Previous travel behavior studies have been critiqued for singling out the effects of precipitation, temperature, and wind instead of considering the co-occurrence of weather parameters (Böcker, Dijst, et al., 2013a). While studies of outdoor thermal comfort have successfully employed composite thermal indices, they failed to consider how pedestrians navigate urban spaces and to what extent might that be affected by their perception of thermal comfort (Jia et al., 2022). We seek to address both sets of concerns by bridging the literatures of outdoor thermal comfort and travel behavior in this study.

In their review of travel behavior studies exploring the effect of weather, Böcker, Dijst, et al. (2013a) report several limitations. First, the majority of studies focus on the effect of weather on mode choice or trip generation. Other travel behaviors are rarely considered. Second, the reviewed studies often use daily weather data, which does not always reflect actual weather at the moment a trip is taking place. Third, most travel behavior studies single out the effects of specific weather parameters without considering their co-occurrence. Moreover, they do not account for the relationship between atmospheric conditions and physiological processes in the human body, which influence the way in which the human body perceives temperatures. Although relatively common in the health and thermal comfort literatures, indicators of perceived temperatures, such as the physiological equivalent temperature (PET) and the Universal Thermal Climate Index (UTCI), have rarely been used in travel behavior research. Fourth, mode choice studies tend to adopt a mono-modal perspective, which is often not the case in reality. When it comes to walking, it can be a mono-modal trip (i.e., a direct walk from the origin to the destination) or a first-/last-mile connection to public transport. Even the relatively short sections of waiting at or traveling to/from public transit stations are subject to heat exposure for pedestrians.

In this paper, we focus exclusively on pedestrian route choice to explore how heat affects pedestrian decision-making in choosing between different routes to the same destination. We hope to extend our collective understanding of the effect of weather on travel behavior by considering a less well-explored behavioral dimension (i.e., route choice). Instead of using daily weather data, we use historical data on mean radiant temperature, wind speed, relative humidity, and near-surface air temperature to compute an hourly composite heat measure called the Universal Thermal Climate Index (UTCI) for every unique trip start time. UTCI has been found to be significantly associated with pedestrians' thermal sensation and thermal comfort (Jia et al., 2022). By computing UTCI values that are matched to the trip start times, we thus address both the second and third limitations highlighted above. Finally, in addition to exploring the effect of heat on pedestrian route choice, we also evaluate how heat stress affects pedestrian accessibility to transit stations to demonstrate the significant extent to which high levels of heat reduces pedestrians' willingness to walk.

3. Research methods

We outline our research methods in this section. First, we discuss our choice of study area — the City of Boston, MA — along with the local cultural, climatic, and policy contexts. We then provide an overview of the data we used in this study. The primary data source was a time-stamped year-long dataset of pedestrian trajectories in Boston. We supplemented this with additional data on various route attributes, including thermal comfort along the route at the time of the trip. Finally, we describe the analytical framework using which we evaluated pedestrian route choice preferences and assessed the effect of heat after controlling for other route attributes.

3.1. Study area

We chose to focus on Boston, MA for this study. The City of Boston in the Commonwealth of Massachusetts is home to over 650,000 residents distributed over about 50 square miles (125 sq. kilometers), which makes it the third-most densely populated large American city. The Massachusetts Bay Transportation Authority (MBTA), which is the first public transportation agency in the country, serves the Greater Boston region. Almost 17 in 100 Boston commuters bike or walk to work, which is tied highest nationally with Washington D.C.[1] This can be partially attributed to the high quality of walkability in the city. WalkScore, a popular pedestrian accessibility indicator, assigned Boston a city-wide average score of 83, which is ranked third in the nation after San Francisco (89) and New York City (88).[2] Much of the built environment in Boston pre-dates the automobile. The urban form, street layouts, and land-use patterns historically evolved around residents who primarily walked. Boston is also largely level and enforces a city-wide 25 mph default speed limit.[3] The City of Boston was an early adopter of 'Shared Streets' and 'Open Streets' campaigns during the COVID-19 pandemic that aimed to prioritize pedestrian and biking activity over automobiles. Although similar campaigns initiated by most cities have not been sustained over time, Boston has expanded these programs significantly, while embedding them into synergistic sustainable transportation policy efforts with specific attention to equitable recovery and mobility needs of vulnerable groups (Basu, Ferreira, 2021b; Glaser & Krizek, 2021).

The city experiences a mix of humid subtropical and continental climates, with summers being warm and humid while winters are cold and stormy. Despite the moderating influence of the Atlantic Ocean, peak summer temperatures in Boston can reach as high as 95 °F (35 °C). Similar to elsewhere in the world, Boston is also experiencing steadily rising temperatures due to climate change. Two summers ago (in 2021), Boston experienced more than 40 days of temperatures over 90 °F (32 °C). The city experienced a heatwave as we were writing this paper (during the summer of 2023), which Mayor Wu responded to by declaring a heat emergency.[4] The City has been exploring various strategies to address extreme heat (such as parks, street trees, green roofs, and library cooling centers) through the 'Climate Ready Boston' initiative..[5] In their report, the City acknowledged that heat depends on perceptive experience, rather than the actual temperature. Instead of using federal data, the City created new climate datasets and modeling that can tell a truer picture of what heat feels like on the ground in different conditions. This study is partly motivated by these efforts to improve pedestrian mobility and address the effects of adverse weather conditions brought about by climate change. Our work aims to contribute to a better understanding of how pedestrians perceive extreme heat and to what extent might their accessibility to important destinations, such as public transit, be reduced.

[1] https://www.boston.gov/getting-around-boston

[2] https://www.walkscore.com/cities-and-neighborhoods/

[3] https://www.boston.gov/departments/transportation/25-boston

[4] https://www.boston.gov/news/mayor-wu-declares-heat-emergency-july-27-28-opens-15-bcyf-cooling-centers-all-residents

[5] https://www.boston.gov/environment-and-energy/climate-ready-boston

3.2. Data

Our primary dataset for this study is a collection of pedestrian GPS traces captured from May 2014 to May 2015 in Boston, MA using a popular activity-oriented smartphone application. In previous work using the same dataset, we have demonstrated how different built environment characteristics affect pedestrian route choice behavior and accessibility (Basu & Sevtsuk, 2022). We adopted a similar methodological approach in this study and add a measure of thermal comfort (UTCI) as an additional explanatory variable. The raw GPS traces were matched with TIGER/Line shapefiles of street centerlines provided by the U.S. Census Bureau using the Hidden Markov model. We also constructed a choice set of up to three alternatives for every pedestrian trip (chosen route) using a constrained enumeration approach. This led to a 'clean' sample of 11,165 chosen routes that we had used in our previous research, which the reader is invited to refer to for further details on the map-matching and choice set generation procedures. Out of these 11,165 chosen routes, we chose to focus only on trips that were made during the summer and early fall (June 7 to October 17) in this study, as the city is likely to experience high heat levels during this time period. This 'summer trip' sample contained 2165 chosen routes, representing about a fifth (19.4 %) of the full sample. Fig. 1 shows the spatial distribution of pedestrian trips for both the full sample ($N = 11{,}165$) and the summer sample ($N = 2165$). We did not observe any systematic spatial bias in the routes pedestrians chose to walk along during the summer compared to the rest of the year.

We then computed various route attributes for both the chosen routes (N = 2165) and the alternative routes in the choice set (up to three for every chosen route) — route length, number of turns, sidewalk width, amenities, Sky View Factor (SVF), and Normalized Difference Vegetation Index (NDVI). We computed the route length directly from the GPS trajectories, while a turn was defined as a change in angle of at least 45 degrees between two successive street segments. The sidewalk width for the route was computed as the weighted average of sidewalk widths associated with street segments, where the segment lengths were used as weights. Amenities were sourced from the InfoGroup dataset on business establishments across North America. The Sky View Factor (SVF) was computed using Google Street View imagery, whereby SVF (0 to 1) acts as a proxy variable to capture the sense of enclosure and shading along a route (SVF = 1 denotes a completely enclosed street canyon). The Normalized Difference Vegetation Index (NDVI) was computed using PlanetScope satellite imagery (available freely to researchers) at a 3-meter resolution, whereby NDVI (−1 to +1) denotes the presence and intensity of vegetation, if present, along a route (Huang et al., 2021). Additional details are available in Basu and Sevtsuk (2022) for interested readers.

This study adds a new explanatory variable to the mix — the Universal Thermal Climate Index (UTCI), which is a measure of heat stress.

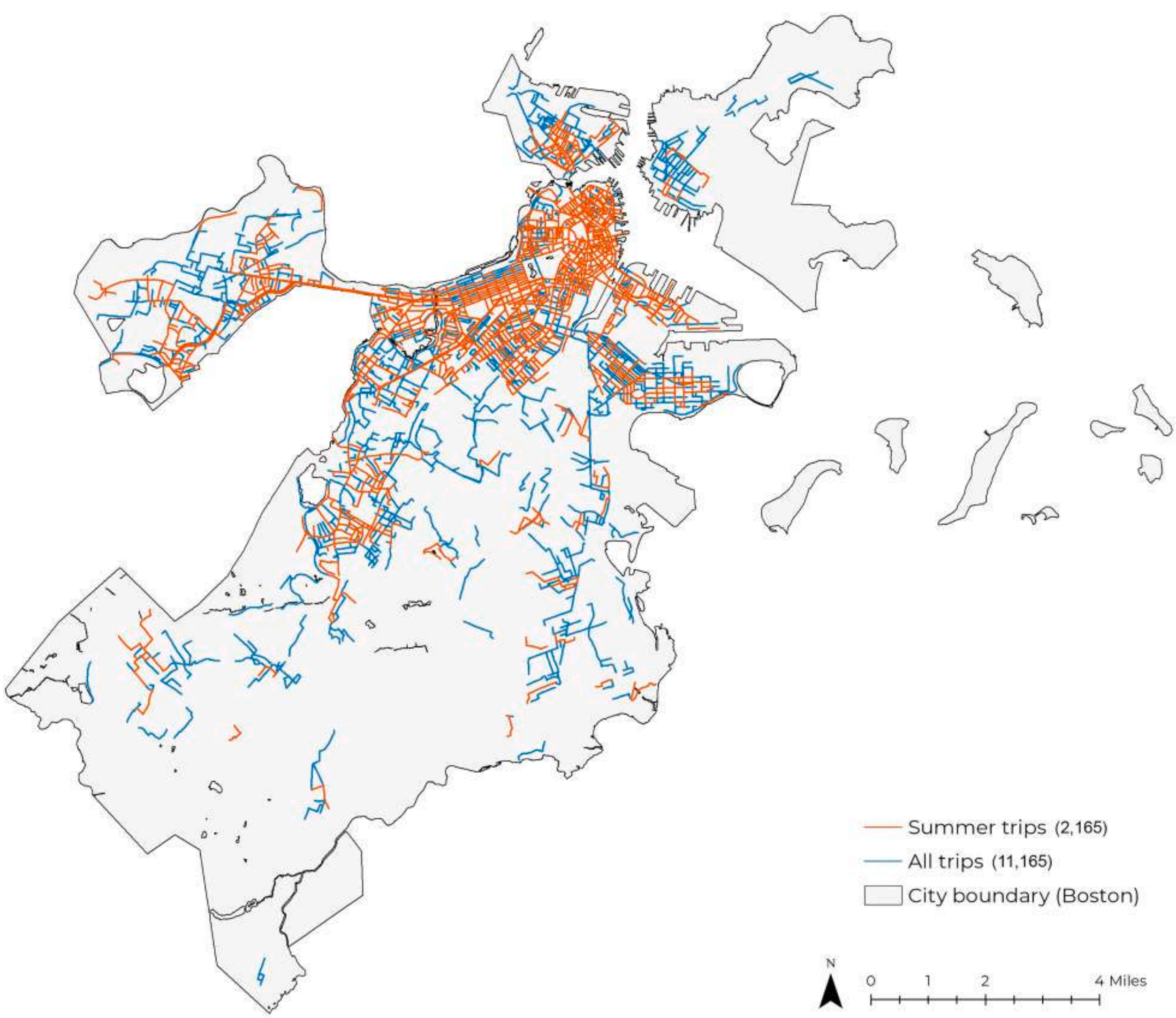

Fig. 1. Spatial distribution of pedestrian trips.

UTCI is a bioclimatic index for describing the physiological comfort of the human body under specific meteorological conditions (Jendritzky et al., 2012). UTCI measures the apparent temperature our bodies would feel under the specified environmental conditions, considering the interplay of air temperature, wind speed, humidity, and mean radiant temperature (Fiala et al., 2012). These four factors influence heat exchange between the body and the environment, affecting the body's heat balance and overall thermal sensation. Both air temperature and relative humidity are measured at 2 meters above ground level, while wind speed is usually measured 10 meters above ground level. Mean radiant temperature is influenced by direct and diffuse solar radiation, as well as long-wave radiation emitted by the sky, ground, and surrounding surfaces. UTCI has been found to overcome the limitations of previous heat indices owing to the combination of an advanced thermo-physiological model and a state-of-the-art clothing model (Di Napoli et al., 2021).

UTCI is measured in degrees Celsius (°C), and is interpreted using a scale of multiple thermal stress categories corresponding to specific physiological responses to the thermal environment. These categories range from extreme heat stress for values above +46 °C to extreme cold stress for values below −40 °C. Between these two extremes, there are categories for very strong, strong, moderate and slight heat and cold stress. A separate category for no thermal stress is defined when UTCI is between +9 °C and + 26 °C. As the focus of this study is on heat stress, we are interested only in trips (and locations) where UTCI exceeds +26 °C. UTCI has been applied widely in various fields, including urban planning, epidemiology, and climate change research. Studies have used

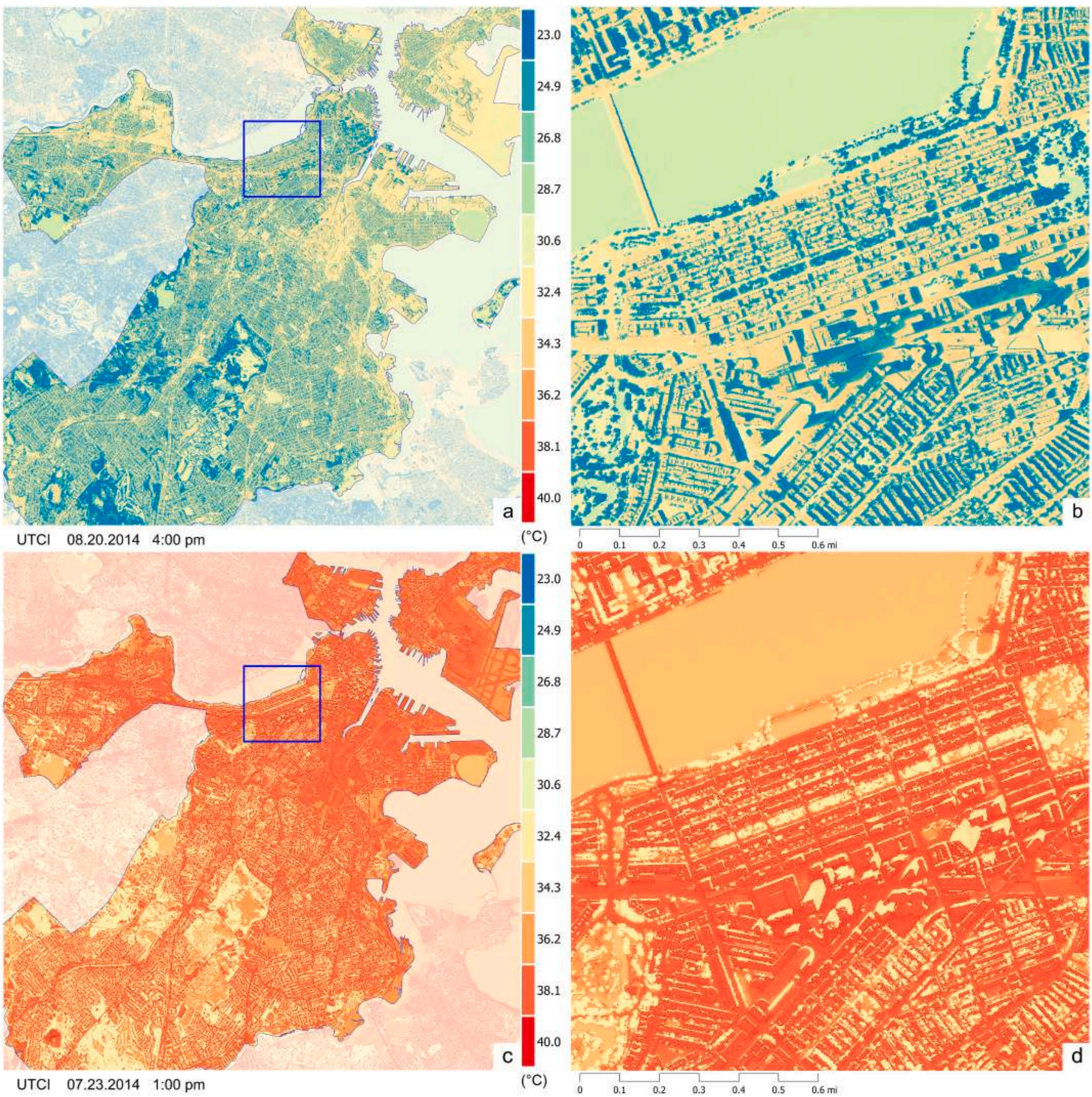

Fig. 2. Spatiotemporal variation in UTCI for (a, b) a typical summer day — 4:00 pm on August 20, 2014; and (c, d) the hottest summer day — 1:00 pm on July 23, 2014. Sub-figures (a) and (c) cover the entire study area of Boston, MA; (b) and (d) represent a zoomed-in focus on Back Bay.

UTCI to explore the association between outdoor thermal comfort and human well-being, and develop adaptation and mitigation policies and climate action plans (Krüger, 2021; Setiawati et al., 2021). However, as mentioned earlier, exploring the effect of urban microclimate on travel behavior is still in a relatively nascent stage. This study aims to contribute to this growing literature and improve our understanding of pedestrians may adapt to heat stress by choosing different routes to walk along that offer greater thermal comfort.

We calculated UTCI for this study using the four main environmental variables, i.e., air temperature, relative humidity, wind speed, and mean radiant temperature. We computed mean radiant temperature at a 2.5 meter resolution using the SOLWEIG (Solar and Longwave Environmental Irradiance Geometry) model on remote sensing data, specifically the 2015–16 LARIAC LiDAR dataset openly available from the NOAA Digital Coast Data Access Viewer. We converted the LiDAR point cloud to a Digital Surface Model (DSM) accounting for both buildings and trees, as well as a Digital Terrain Model (DTM) for the ground. We combined these data with an open-source Land Use Land Cover (LULC) dataset for 2016 obtained from the Massachusetts Bureau of Geographic Information (MassGIS) to compute the mean radiant temperature. This additional step helps us assign different values of albedo and emissivity to the different land cover classes, such as paved (asphalt and cobblestone), grass, bare soil, and water.

We then used the ERA5 dataset, produced by the Copernicus Climate Change Service (C3S) at the European Center for Medium-Range Weather Forecasts (ECMWF), to compute air temperature and humidity at 2 meters above ground level, as well as wind speed at 1.5 meters above ground level, with hourly temporal resolution. Readers should note that mean radiant temperature is the only variable among the four that varies both spatially and temporally; air temperature, relative humidity, and wind speed are spatially constant, but vary hourly. When all four components are combined, we obtain hourly UTCI values at a 2.5 meter resolution. As our pedestrian trip data (GPS trajectories) are timestamped, we computed average UTCI values for each route corresponding to the specific time and day on which the trip was undertaken.

Fig. 2 shows the spatiotemporal variation in UTCI, calculated hourly at a 2.5 meter resolution, before we computed average values for each pedestrian route. The top panel represents a typical summer day — 4:00 pm on August 20, 2014 — when the temperature was 22.6 °C with 64 % relative humidity (resulting in a Heat Index of 73 °F). We can identify several cooler locations (as denoted through bluer shades) where there is more urban greenery or shadows cast by tall buildings. The panel on the bottom represents the hottest summer day — 1:00 pm on July 23, 2014 — when the temperature was 29.6 °C with 61 % relative humidity (Heat Index = 90 °F). We can observe similar spatial variation but with an area-wide increase in average UTCI. The hottest locations experience close to 40 °C, while the coolest locations are around 32 °C (as opposed to 23 °C during a typical summer day). The zoomed-in right panel (subfigures (b) and (d)) demonstrate the importance and value of computing heat stress at a high spatial resolution, as UTCI can vary between two adjacent blocks or even between two sidewalks on opposite sides of the same road.

The effect of urban greenery on mitigating heat stress is further illustrated in Fig. 3. We show the street segment-level UTCI variation both spatially (due to the built and natural environment) and temporally (a typical summer day vs. the hottest summer day). We find that locations like Commonwealth Avenue and Marlborough Street, which have significant amounts of urban greenery, experience considerably lower heat. Locations that are much more built-up with lesser greenery, such as Boylston St, are understandably more heat-stressed. On a typical summer day, urban greenery can be the difference between a location experiencing thermal stress (UTCI > +26 °C) or not. Although all street segments in the zoomed-in area experience thermal stress on the hottest summer day, the lack of urban greenery can elevate heat stress levels from moderate to strong, or even extreme in some cases.

We know from the literature that people are more sensitive to adverse weather for recreational and leisure trips compared to

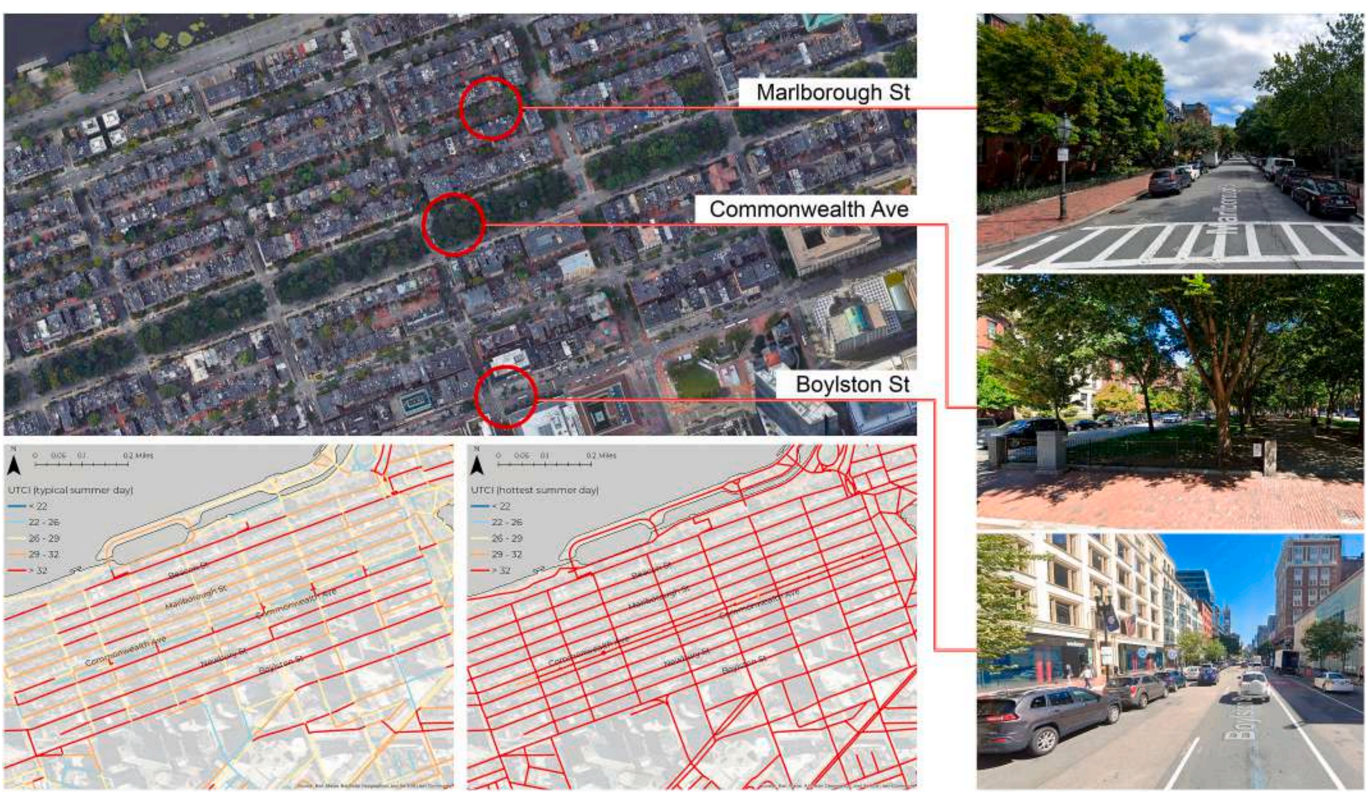

Fig. 3. Effect of urban greenery on UTCI and thermal stress.

utilitarian trips. Pedestrians who are commuting to work, dropping a child off at school or daycare, carrying heavy grocery bags, or trying to make a pre-scheduled appointment (such as a doctor's visit) may not be able to consider alternative routes. Some pedestrians may be creatures of habit and prefer walking along the same familiar route. Others may not have the time to experiment and simply want to get to their destination as quickly as possible. Thermal comfort is unlikely to play a role in pedestrian decision-making in such cases. Therefore, in an effort to parse pedestrian trips where a choice set does indeed exist, we considered focusing exclusively on summer trips that provided at least one alternative that had a higher average UTCI value at the same time on the same day. We call this dataset the 'UTCI-flexible' dataset because pedestrians had the flexibility to switch to a different alternative that had higher UTCI than the chosen route, but did not. We further filtered this dataset to create a subset of summer day trips that were conducted between 9:00 am and 7:00 pm and are UTCI-flexible as well. The descriptive statistics of various route attributes for these three datasets are presented in Table 1. Although the sample sizes differ, we did not observe any meaningful or statistically significant difference in route attributes other than UTCI across the three datasets. Restricting the sample to only day trips (9 AM - 7 PM) understandably results in an increase in the mean UTCI from 22.7 °C to 26.3 °C.

3.3. Analytical framework

Discrete choice models have been used for decades in travel behavior research to explain behavioral decisions such as mode and route choice, among others (Ben-Akiva & Lerman, 1985). The most commonly used discrete choice model is the multinomial logistic regression (MNL) model. However, prior studies have noted that the MNL model is not well-suited for route choice applications, as several alternative routes may overlap among themselves as well as with the chosen route (Basu & Sevtsuk, 2022; Sevtsuk et al., 2021). In this study, we model the pedestrian route choice decision-making process using a path-size logit (PSL) model. The PSL model builds on the simpler MNL model by including a path size correction term to account for the correlation resulting from the overlap between alternative routes (Ben-Akiva & Bierlaire, 1999). The general formulation of the PSL model is:

$$U_i = \beta_{il}.l_{ij} + \sum_{j=1}^{6} \beta_{ij}.X_{ij} + \beta_{i,PS}.ln(PS_i) + \epsilon_i \qquad (1)$$

where U_i is the random utility of route i; β_{il} represents the coefficient for route length; β_{ij} represents a vector of j choice coefficients corresponding to the different route attributes X_i ($j = 6$ in this study — turns, sidewalk width, amenities, Sky View Factor, Normalized Difference Vegetation Index, and UTCI); and PS_i is the path size factor for route i. The error term (ϵ_i) is assumed to follow a Type-I Generalized Extreme Value (GEV) distribution, also known as a Gumbel distribution, and is independently and identically distributed (i.i.d.) across the alternatives. The variance of the error term (ϵ_i) is $\pi^2/(6\mu^2)$, where μ is the scale parameter of the Gumbel distribution. The path size factor is computed as follows:

$$PS_i = \sum_{m \in \tau_i} \frac{L_m}{L_i} \left(\frac{1}{\sum_{k \in C_n} \delta_{mk}} \right) \qquad (2)$$

where τ_i is the set of links (or segments) on route i; L_m is the length of link m; δ_{mk} is a binary indicator for link-route overlap (i.e., $\delta_{mk} = 1$ when link m is on route k, and $\delta_{mk} = 0$ otherwise); and $\sum_{k \in C_n} \delta_{mk}$ is the number of routes in choice set C_n that share link m.

Eq. (1) can be thought of as a model formulation expressed in 'preference space,' since we are directly estimating coefficients for different route attributes. This is the standard approach to model formulation and estimation, following which coefficients for route attributes can be divided by the coefficient of the length (or price) attribute to arrive at willingness-to-walk (or willingness-to-pay) estimates. We can write an equivalent model formulation as follows, where the error term (ζ_i) has a variance of $\pi^2/6$:

$$U_i = \mu.\left(\beta_{il}.l_{ij} + \sum_{j=1}^{6} \beta_{ij}.X_{ij} + \beta_{i,PS}.ln(PS_i) \right) + \zeta_i \qquad (3)$$

We need to assume the scale parameter of the Gumble distribution (μ) to be equal to unity for this model to be identifiable, which is standard practice. There is an alternative approach to model formulation where we can parameterize a fixed-coefficient model in terms of willingness-to-pay (WTP) rather than the choice coefficients, thereby leading to model formulation and estimation in 'WTP space.' The two approaches are formally equivalent, in the sense that any distribution of coefficients translates into some derivable distribution of WTP's, and vice-versa (Train & Weeks, 2005). That being said, the two approaches differ in terms of numerical convenience under any given distributional assumptions. The general practice in travel behavior modeling has been to specify distributions in preference space, estimate the parameters of those distributions, and derive the distributions of WTP from these estimated distributions in preference space. While fully general in theory, this practice is usually limited in implementation by the use of convenient distributions for utility coefficients. Convenient distributions for utility coefficients do not necessarily imply convenient distributions for WTP, and vice-versa (Hensher & Greene, 2011). Researchers have reported that estimating the model in WTP space is a better strategy when the objective is to extract WTP estimates rather than translating the estimates from preference space to WTP values (Daly et al., 2020; Hess et al., 2008). For pedestrian route choice models, the analogous measure of WTP is willingness-to-walk (WTW). Willingness to walk for a route attribute is the ratio of the attribute's coefficient to the length coefficient, as the 'price' for pedestrian trips is the trip distance. Since we are interested in extracting the WTW for different route attributes in this study, we opted to formulate and estimate the pedestrian route choice model in WTW space (see Eq. (4)).

$$U_i = \mu.\beta_{il}.\left(l_{ij} + \sum_{j=1}^{6} \omega_{ij}.X_{ij} + \omega_{i,PS}.ln(PS_i) \right) + \zeta_i \qquad (4)$$

where ω_{ij} represents the willingness-to-walk (WTW) for the $j(=6)$ route

Table 1
Descriptive statistics of actual pedestrian trajectories (chosen routes).

	Summer trips			Summer trips (UTCI-flexible)			Summer day trips (UTCI-flexible, 9 AM - 7 PM)		
	mean	*min*	*max*	*mean*	*min*	*max*	*mean*	*min*	*max*
Length (m)	635.5	202.1	999.9	643.2	202.1	999.9	624.9	226.6	999.9
Number of turns	3.4	2.0	7.0	3.5	2.0	7.0	3.5	2.0	7.0
Amenities	23.8	0	231	25.8	0	231	23.9	0	192
Sidewalk width (ft.)	10.1	0	42.6	10.1	0	42	9.8	0	36.6
Sky View Factor (SVF)	0.61	0.25	0.95	0.61	0.26	0.95	0.58	0.26	0.94
Normalized Difference Vegetation Index (NDVI)	0.25	0.07	0.75	0.25	0.07	0.75	0.25	0.09	0.75
Heat (UTCI)	22.7	9.8	38.3	22.0	9.8	37.3	26.3	12.4	37.3
Sample Size		2165			1361			742	

attributes. For this model to be identifiable, we will need to assume that the choice coefficient for route length (β_l) is equal to unity. Thereby, we will be able to estimate the scale parameter (μ) as well as the WTW for six route attributes, including UTCI, and the path size factor.

The probability that a particular route *i* is chosen from a choice set *C* with *n* alternatives is expressed as follows:

$$Pr(i|C_n) = \frac{exp(U_{in})}{\sum_{j \in C_n} exp(U_{jn})} \quad (5)$$

Since our data are anonymous and do not contain pedestrian characteristics, we are constrained to assume identical WTW values for all pedestrians and cannot control for heterogeneity through logit mixtures. Additionally, we cannot correct for panel effects as we are unable to infer repeated observations for the same individual. We used the PythonBiogeme software for model estimation. Along with WTW estimates, we also computed 'robust' t-statistics by using standard errors that were corrected for heteroskedasticity. We estimated models with different specifications to understand the effect of thermal comfort on pedestrian route choice, both conceptually as well as in terms of improving the model goodness-of-fit. Additionally, we explored whether this effect was non-linear, as previous studies have been critiqued for wrongfully assuming linear relationships between weather and travel (Böcker, Dijst, et al., 2013a).

To translate route choice model estimates into pedestrian accessibility evaluations, we also conducted a walkshed analysis where we constructed catchment areas around 15 MBTA Commuter Rail stations in Boston. We considered four types of walksheds through which the difference between actual geometric distance and perceived distance was highlighted. The first type of walkshed was constructed using the geometric distance along the street network. The second walkshed type pivoted to using perceived distance along the street network, where route attributes other than the UTCI (i.e., turns, sidewalk width, amenities, SVF, and NDVI) were translated to their equivalent walking distance values in the calculation of perceived distance. The third walkshed type also used perceived distance but included the effect of UTCI as well, considering a typical summer day in 2014. We extended this analysis to a fourth walkshed type that included the effect of UTCI on the hottest summer day in 2014. All four walkshed types were constructed using 800 meters as the catchment area network radius. We then compared these walksheds to evaluate the extent to which pedestrian accessibility would be affected by route attributes other than UTCI, and then by UTCI, both on a typical summer day and the hottest summer day. Detailed results of these analyses are presented in the following section.

4. Results and discussion

In this section, we first present the results of various PSL model specifications and discuss the effect of thermal comfort on pedestrian route choice preferences in Boston. This is followed by an exploration of how willingness to walk is affected at different levels of thermal comfort. Finally, we examine how thermal comfort influences pedestrian accessibility to public transit stations owing to the difference between actual (geometric) distance and perceived distance.

4.1. Does heat affect pedestrian route choice?

To understand if heat affects pedestrian route choice in Boston, we included UTCI as an additional explanatory variable in the utility equation on top of the other route attributes (such as turns, sidewalk width, amenities, NDVI, and SVF). The route length coefficient is not reported, but the scale parameter is, because we estimated the route choice model in WTW space. Since UTCI values below 26 °C indicate no thermal stress, only the additional effect of every 1 °C increase in UTCI beyond 26 °C is estimated through the model. For example, if the UTCI for a certain route on a given day is 32 °C, we only consider the contribution of the additional (32–26=) 6 °C toward pedestrian route choice preferences. We tested the effect of UTCI (beyond 26 °C) on pedestrian route choice behavior in Boston using various datasets and specifications (control variables), and report the results in Table 2.

Model (1) includes UTCI as an additional explanatory variable and is estimated using the dataset including all summer trips ($N = 2165$). We find that the perceived distance for UTCI is quite small (6.6 meters/°C) and not statistically significant at a reasonable confidence level. Other effects are consistent with our previous findings (Basu & Sevtsuk, 2022). Each turn is perceived to be equivalent to almost 40 meters, while each amenity reduces the perceived distance by 0.24 meters. An additional foot of sidewalk width decreases the perceived walking distance by almost 3 meters. Exposure to greenery and the open sky are both considered to be attractive for pedestrians during the summer, with 10 % increases in NDVI and SVF translating to reductions in perceived distance by about 25 meters and 10 meters respectively.

Acknowledging that pedestrians may not have the flexibility or desire to think about thermal comfort in their route choice decision-making process for several types of trips (such as utilitarian or time-sensitive trips), we estimate Model (2) with the same specification but on the 'UTCI-flexible' dataset ($N = 1361$). As mentioned earlier, this dataset contains a subset of summer trips that have at least one alternative route in the choice set with a higher UTCI than the actual chosen route. We see from Model (2) that the effect of UTCI is now considerably high and statistically significant ($p < 0.001$), while the other effects remain consistent with what we observed in Model (1). The perceived walking distance increases by 104 meters for every 1 °C increase in UTCI beyond the thermal stress threshold of 26 °C. This finding echoes the literature in suggesting that pedestrians may be more flexible about certain types of trips, where they adapt to extreme heat by choosing routes with higher thermal comfort. However, on the flip side, for trips where pedestrians are relatively inflexible, walking along routes that experience high heat stress can feel quite onerous and punishing.

In addition to finding a meaningful and statistically significant effect of UTCI, we also wanted to test whether adding UTCI as an additional explanatory variable to the pedestrian route choice model improved the model goodness-of-fit. Model (3) resembles Model (2) in every way except for the omission of UTCI. We find that the model goodness-of-fit (as measured by McFadden's pseudo R-squared value) decreases from 0.850 to 0.832, which is an absolute difference of almost 2 percentage points. We also wanted to test whether our findings would hold if we further honed in on trips that were made during the day (between 9 AM and 7 PM), as this time period is when heat stress is most prominently felt. Therefore, we repeated the same estimation exercises from Models (2) and (3) but on a subset of the 'UTCI-flexible' dataset that included only day trips ($N = 742$). Models (4) and (5) provide consistent findings. UTCI remains statistically significant ($p < 0.001$), although the perceived distance effect reduces from 104 meters to 80.8 meters. Including the UTCI as an additional explanatory variable on top of the other controls improves the model goodness-of-fit by 1.6 percentage points.

Route length and the number of turns have been reported to be the two most important variables for pedestrian route choice as they explain a significant portion of the variation in preferences (Sevtsuk & Basu, 2022). To isolate the contribution of UTCI to the model goodness-of-fit, we estimated Models (6) and (7). Model (6) includes only length and turns as explanatory variables, which explain 81.5 % of the variation. We build on this by including UTCI in Model (7) and find the goodness-of-fit to increase by 2.1 percentage points. Thus, we can conclude that UTCI seems to be the most important variable in influencing pedestrian route choice after route length and turns, especially during the summer when heat stress can be a major issue.

4.2. How does heat affect willingness to walk?

We established in the previous sub-section that thermal comfort

Table 2
Different WTW-space specifications of path-size logit models of pedestrian route choice in Boston[a].

	(1)			(2)			(3)			(4)			(5)			(6)			(7)		
	Est.	t-stat	Signif.	Est.	t-stat	Signif.	Est.	t-stat	Signif.	Est.	t-stat	Signif.	Est.	t-stat	Signif.	Est.	t-stat	Signif.	Est.	t-stat	Signif.
UTCI (+1 °C, above 26 °C)	6.2	0.66		104	3.99	***				80.8	3.06	***							85.5	3.46	***
Turns (+1)	39.8	9.54	***	36.6	6.94	***	39.6	7.5	***	43.5	5.67	***	46.3	6.12	***	45.6	5.99	***	44.3	5.81	***
Sidewalk width (+1 ft.)	−2.68	−1.96	**	−1.81	−0.86		−2.31	−1.19		−2.86	−0.92		−3.4	−1.21							
Amenities (+1)	−0.24	−1.29	~	−0.37	−1.93	**	−0.11	−0.53		−0.26	−1.07		0.01	0.05							
NDVI (+10 %)	−24.4	−2.67	***	−20.50	−1.66	*	−19	−1.63	*	−24.6	−1.45	~	−28	−1.85	*						
Sky View Factor (+10 %)	−10.3	−1.38	~	−45.2	−4.3	***	−22.5	−2.49	***	8.92	0.67		34.5	2.89	***						
ln(Path Size)	−849	−16.1	***	−767	−12.2	***	−820	−12.7	***	−828	−8.98	***	−872	−9.25	***	−859	−9.43	***	−827	−8.96	***
Scale (μ)	−0.015	−16	***	−0.016	−12.4	***	−0.015	−12.8	***	−0.015	−8.29	***	−0.015	−8.67	***	−0.015	−9.29	***	−0.015	−8.77	***
Dataset	Summer trips			Summer trips (UTCI-flexible)			Summer trips (UTCI-flexible)			Summer day trips (UTCI-flexible)			Summer day trips (UTCI-flexible)			Summer day trips (UTCI-flexible)			Summer day trips (UTCI-flexible)		
Sample size	2165			1361			1361			742			742			742			742		
Adjusted rho-squared	0.818			0.850			0.832			0.833			0.817			0.815			0.836		
Log-likelihood	−427.1			−226.0			−254.3			−132.8			−147.3			−153.5			−134.7		
Akaike Information Criterion (AIC)	870.2			468.0			522.7			281.7			308.6			326.8			295.7		

[a] ***Note:*** Willingness-to-walk (WTW) estimates, robust t-statistics, and corresponding significance levels (~$p < 0.2$; * $p < 0.1$;** $p < 0.05$; *** $p < 0.01$) are reported. All weighted mean variables are calculated using link lengths as weights.

Table 3
Equivalent walking distance effect of heat.[a]

	(1)			(2)		
	Est.	t-stat	Signif.	Est.	t-stat	Signif.
UTCI (+1 °C, above 26 °C)	80.8	3.06	***			
UTCI (+1 °C, 26 °C to 29 °C)				21.7	2.68	***
UTCI (+1 °C, 29 °C to 32 °C)				44.0	1.62	*
UTCI (+1 °C, above 32 °C)				64.3	1.66	*
Turns (+1)	43.5	5.67	***	45.8	5.78	***
Sidewalk width (+1 ft.)	−2.86	−0.92		−3.16	−1.01	
Amenities (+1)	−0.26	−1.07		−0.30	−1.30	~
NDVI (+10 %)	−24.6	−1.45	~	−28.5	−1.70	*
Sky View Factor (+10 %)	8.92	0.67		14.4	1.11	
ln(Path Size)	−828	−8.98	***	−860	−8.86	***
Scale (μ)	−0.015	−8.29	***	−0.015	−8.65	***
Sample size		742			742	
Adjusted rho-squared		0.833			0.832	
Log-likelihood		−132.8			−131.7	
Akaike Information Criterion (AIC)		281.7			283.4	

[a] ***Note:*** Willingness-to-walk (WTW) estimates, robust t-statistics, and corresponding significance levels (~ $p < 0.2$; * $p < 0.1$;** $p < 0.05$; *** $p < 0.01$) are reported. All weighted mean variables are calculated using link lengths as weights.

plays an important role in influencing pedestrian route choice preferences during summer. The perceived distance effect of heat stress was found to be just over 80 meters for every 1 °C increase in UTCI beyond 26 °C. However, this effect is an average estimate uniformly distributed over the heat stress spectrum (UTCI > 26 °C). It is likely that pedestrians perceive higher heat stress levels to be more onerous and the effect of UTCI is non-linear. To test this hypothesis, we estimated two models on summer day trips from the 'UTCI-flexible' dataset (see Table 3). Model (1) assumes the effect of UTCI to be linear and uniform, while Model (2) treats the effect of UTCI as non-uniform. We created categories of heat stress based on UTCI thresholds. When UTCI is between 26 °C and 32 °C, moderate heat stress is felt. Strong heat stress is classified by UTCI values between 32 °C and 38 °C. Boston did not experience such high temperatures frequently during the 2014 summer, as evidenced by the average UTCI value in our data being 26.3 °C while the maximum value was 37.3 °C. Therefore, instead of using these widely defined heat stress categories, we used smaller ranges to explore the non-linearity of the UTCI effect. In particular, we constructed three heat stress categories — (a) 26 °C to 29 °C, (b) 29 °C to 32 °C, and (c) above 32 °C.

We find from Table 3 that the model results support our hypothesis. The effects are indeed non-uniform and unsurprisingly increasing. For the lowest heat stress category (26 °C to 29 °C), each degree increase in UTCI is perceived to be equivalent to 21.7 meters of additional walking. The perceived distance effect is almost double (44 meters) for the next category (29 °C to 32 °C). Beyond 32 °C, every degree increase in UTCI leads to the perceived walking distance increasing by 64.3 meters. It is interesting to observe that the effect sizes increase (almost) linearly across these three categories. Unfortunately, the Boston data from 2014 do not have enough variation beyond 32 °C to allow us to explore how the perceived distance effect evolves further. We believe that the curve is likely to be exponential and the data show us only the left part of the exponential curve, which closely resembles a linear curve. Our belief stems from the expectation that, after a certain heat threshold, the perceived distance effect will become large enough to overpower the willingness to walk, thereby inducing the trip-maker to forgo the trip or opt for alternative modes. However, without more variation in the data, we cannot confirm this particular hypothesis. Nonetheless, we can conclude that UTCI has a non-uniform effect on perceived walking distance, whereby higher heat stress (as captured through higher UTCI values) is perceived to reduce willingness to walk by a greater extent.

4.3. How does heat affect pedestrian accessibility?

We have thus far demonstrated that thermal comfort affects pedestrian route choice preferences and illustrated the non-uniform nature of this effect. What are the implications of these findings for pedestrian accessibility? To address this question, we conducted a walkshed analysis where we constructed catchment areas around 15 MBTA Commuter Rail stations in Boston. As described earlier, we considered four types of walksheds, based on (a) geometric distance, (b) perceived distance, using route attributes other than UTCI, (c) perceived distance, using UTCI on a typical summer day and other route attributes, and (d) perceived distance, using UTCI on the hottest summer day and other route attributes. These walksheds are shown in Fig. 4.

We summarize the change in pedestrian accessibility detected from this walkshed analysis in Table 4. We consider the walksheds constructed with geometric distance as the baseline and report relative values for the other walkshed types. In addition to calculating the average catchment area across the walksheds around the 15 stations, we also computed the mean total population and non-White population within the catchment areas. This analysis draws on Census Block Group (CBG) estimates of total and non-White population from the American Community Survey (ACS) 2012–2016, since our pedestrian activity data are from 2014. The CBG-level estimates are then distributed to buildings through a proportional split based on built-up volume corresponding to residential land use (including residential components of mixed land use).

We find the catchment area reduces by more than 50 percent when perceived distance is considered instead of network distance. This implies that less than half (44.1 %) of the population can access the transit station within 800 meters of (perceived) walking if we account for route attributes other than simply length — such as turns, sidewalk width, amenities, SVF, and NDVI. When the effect of heat is also considered, a little over a quarter (25.9 %) of catchment area residents can access the station on a typical summer day. Pedestrian accessibility worsens considerably on the hottest summer day, with about only one in ten (9.5 %) residents having access to the station within the widely considered walking-to-transit threshold of 800 meters.

Transit accessibility reduces even more steeply for non-White pedestrians. Without the inclusion of UTCI in the walkshed construction process, non-White accessibility was marginally better than overall accessibility. However, following the consideration of the perceived distance effect of UTCI, non-White accessibility is observed to be worse than overall accessibility by about one percentage point on a typical summer day. While the magnitude of change may seem small, the flip in the comparative assessment suggests that non-White households are more likely to live in neighborhoods that experience higher heat stress (since the effect of UTCI is estimated uniformly across sociodemographic groups owing to data limitations). Disparities in urban heat exposure along both racial and income lines have been reported for several major

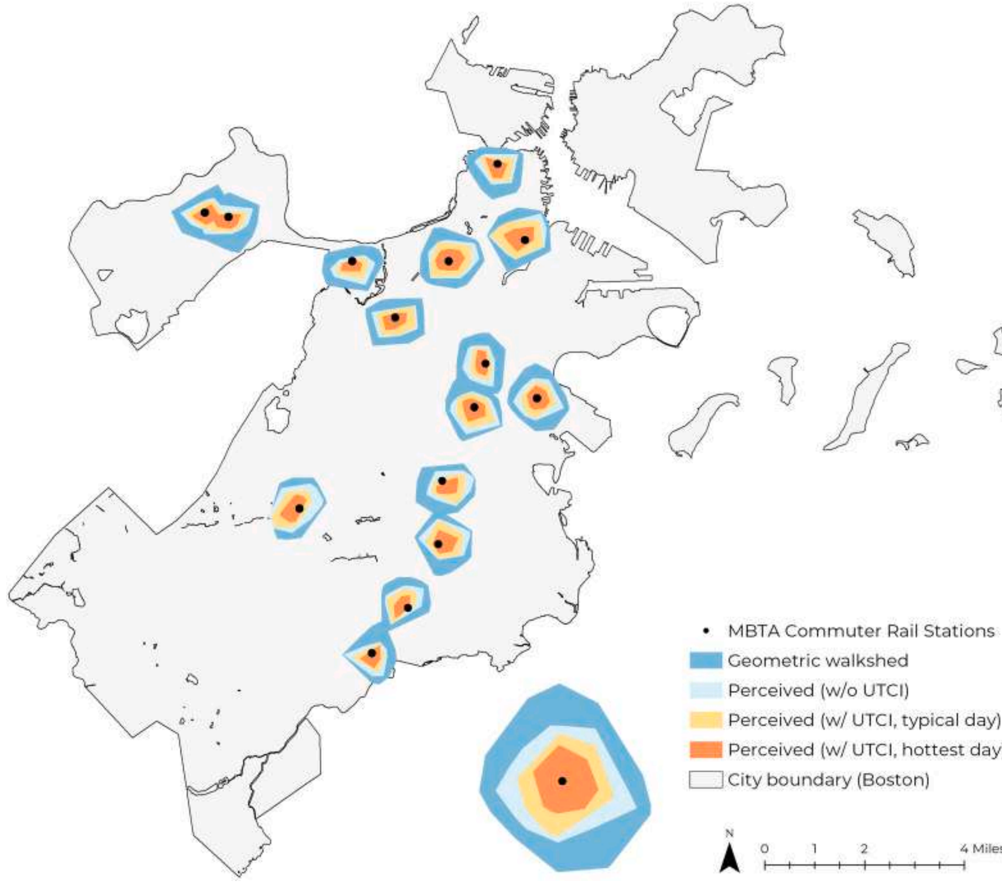

Fig. 4. Walksheds around MBTA commuter rail stations in Boston.

Table 4
Change in pedestrian accessibility due to heat.

Walkshed type	Avg. catchment area	Mean population within walkshed	Mean non-White population within walkshed
Geometric Distance	116.7 ha (100 %)	8936 (100 %)	5281 (100 %)
Perceived Distance (without UTCI)	58.6 ha (50.2 %)	3941 (44.1 %)	2350 (44.5 %)
Perceived Distance (with UTCI, on a typical summer day)	36.2 ha (31.0 %)	2314 (25.9 %)	1326 (25.1 %)
Perceived Distance (with UTCI, on the hottest summer day)	15.6 ha (13.4 %)	849 (9.5 %)	491 (9.3 %)

cities in the U.S. (Chakraborty et al., 2019; Hsu et al., 2021). This could likely be explained by lower levels of vegetation density in neighborhoods with more non-White and lower-income residents (Clarke et al., 2013; Martin et al., 2004). Thus, we can conclude from the walkshed analysis that heat stress significantly reduces pedestrian accessibility. Moreover, non-White pedestrians are affected to a greater extent likely due to systemic disparities in access to affordable housing and climate mitigation measures (such as vegetation).

The pedestrian accessibility values reported and discussed above are averaged across the catchment areas around the 15 commuter rail stations in Boston. To further illustrate the effect of the built environment on pedestrian accessibility, we focus on two particular stations that are proximate to each other on the Fairmount Line — Newmarket and Uphams Corner (see Fig. 5). The catchment area around Newmarket is largely non-residential, with only 1868 residents living within 800 meters (geometric distance) of the station. On the other hand, 10,883 residents live within 800 meters (geometric distance) of the Uphams Corner station. When we consider the effect of the built environment, the catchment areas shrink to 325 residents (17.4 %) for Newmarket and 6174 residents (56.7 %) for Uphams Corner. While pedestrian accessibility to Uphams Corner is well above the average (44.1 %), the corresponding accessibility to Newmarket takes a much greater hit owing to the built environment around the station not being pedestrian-friendly. Upon further considering the effect of heat stress on a typical summer day, only 42 residents (2.2 %) and 4240 residents (39.0 %) are able to access Newmarket and Uphams Corner within a perceived walking distance of 800 meters. On the hottest summer day, none of the residents around Newmarket can access the station within this threshold, while 1626 residents (14.9 %) can access Uphams Corner. Similar to our previous observation, we note that the pedestrian-friendly built environment and ample urban greenery around Uphams Corner influence pedestrian accessibility to be much higher than the average, while the converse is true for Newmarket.

5. Conclusion

In order to simultaneously make progress toward public health and environmental sustainability goals, many cities are trying to veer away from automobile-oriented planning in favor of more sustainable modes of transportation. However, these laudable efforts to transition to sustainable mobility are being challenged by the acceleration of both the intensity and frequency of adverse weather conditions globally. Heatwaves, in particular, affect human mobility, especially for modes that are exposed to the open air such as walking and biking. Pedestrians may

Fig. 5. Walksheds around two MBTA commuter rail stations in Boston - Newmarket and Uphams Corner - with vastly different built environments.

be exposed to high levels of heat stress on hot summer days. When feasible, they may try to adapt by seeking alternative routes that offer better thermal comfort. In other cases, they may choose to switch to a private vehicle (which has air conditioning) or forgo the trip entirely. The consequences of both these decisions are concerning. Pedestrians switching to car travel will undermine the sustainable mobility transition, while forgone trips can lead to worse quality of life outcomes. It is thus critical to better understand how heat affects pedestrian behavior and accessibility, so that climate adaptation and mitigation strategies can be better targeted to support walking as a mode of transport in its own right but also as a first-/last-mile connection to public transit.

In this study, we used a dataset of pedestrian activity in Boston, MA from 2014 to explore the effect of heat stress on pedestrian route choice preferences. We focused only on pedestrian trips undertaken during the summer. In addition to several route attributes (such as length, turns, sidewalk width, amenities, NDVI, and SVF), we also included a measure of heat stress (UTCI) as an explanatory variable. Using path-size logistic regression models with different specifications, we established that heat stress (UTCI) has a considerable and statistically significant effect on the perceived walking distance. We also found that the effect was non-uniform and possibly exponential, with every degree increase in UTCI perceived to be more onerous across increasing heat stress categories. We used a UTCI threshold of 26 °C, as is widely established, to classify heat stress in this study. However, we expect this threshold to vary across the world, as people living in a distinctly hotter climate may be more used to heat. More comparative studies from different climatic and geographical contexts, but with the same methodological and data collection techniques, are required to further explore how pedestrians modify their travel behavior to adapt to heat.

Additionally, we illustrated the extent to which heat stress can reduce pedestrian accessibility to important destinations, such as public transit. The reduction was quite pronounced on a typical summer day, with an even sharper reduction on the hottest summer day. Non-White residents were observed to have lower accessibility levels compared to all pedestrians, likely because of disparities in urban heat exposure. Our findings can be translated to the development of new planning guidelines for improving transit-oriented development (TOD) neighborhoods. The manner in which we included thermal comfort in the cost function of each street segment can be extended to design and plan climate-sensitive walking networks. A routing engine, along the lines of existing applications such as Google Maps or Waze, could be created to provide pedestrians with real-time recommendations for routes with high thermal comfort.

We suggest future studies to explore the role of personal, trip, and geographical characteristics as a mediating effect on the link between weather and travel behavior. This was a limitation of our study as our data were anonymous, which hindered us from inferring any information about the person walking or any background context about the trip. The potentially varying importance of weather for different population groups in different geographical contexts remains largely unaddressed. We recommend travel surveys, which are usually designed without any consideration of weather effects, be modified so that researchers can explore these questions with better data and greater rigor. We also urge researchers to link the relationship between weather and travel behavior to physical and mental health, emotions, and well-being.

Even though the data are from almost a decade ago and the study area (Boston, MA) experiences relatively mild summers, our findings highlight the importance of incorporating heat into transportation planning and urban design frameworks. Summers in Boston have certainly gotten warmer since 2014, as they have elsewhere in the world. Rising temperatures and the consequent effects on accessibility call for thinking about climate mitigation strategies that can aid the sustainable mobility transition and enhance livability. Our transportation and land use policies have created disparities in urban heat exposure, which are likely to be further exacerbated without providing additional supportive measures for vulnerable communities. If we fail to act soon, not only do we endanger pedestrians walking to critical destinations, but also transit ridership that is facilitated by first-/last-mile walk connections.

CRediT authorship contribution statement

Rounaq Basu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nicola Colaninno:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Aziz Alhassan:** Formal analysis, Investigation. **Andres Sevtsuk:** Conceptualization, Data curation, Writing – review & editing.

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.

Data availability

The authors do not have permission to share data.

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