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Heat exposure during outdoor activities in the US varies significantly by city, demography, and activity

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ABSTRACT

Environmental heat is a growing public health concern in cities. Urbanization and global climate change threaten to exacerbate heat as an already significant environmental cause of human morbidity and mortality. Despite increasing risk, very little is known regarding determinants of outdoor urban heat exposure. To provide additional evidence for building community and national-scale resilience to extreme heat, we assess how US outdoor urban heat exposure varies by city, demography, and activity. We estimate outdoor urban heat exposure by pairing individual-level data from the American Time Use Survey (2004–2015) with corresponding meteorological data for 50 of the largest metropolitan statistical areas in the US. We also assess the intersection of activity intensity and heat exposure by pairing metabolic intensities with individual-level time-use data. We model an empirical relationship between demographic indicators and daily heat exposure with controls for spatiotemporal factors. We find higher outdoor heat exposure among the elderly and low-income individuals, and lower outdoor heat exposure in females, young adults, and those identifying as Black race. Traveling, lawn and garden care, and recreation are the most common outdoor activities to contribute to heat exposure. We also find individuals in cities with the most extreme temperatures do not necessarily have the highest outdoor heat exposure. The findings reveal large contrasts in outdoor heat exposure between different cities, demographic groups, and activities. Resolving the interplay between exposure, sensitivity, adaptive capacity, and behavior as determinants of heat-health risk will require advances in observational and modeling tools, especially at the individual scale.

1. Introduction

Cities face warmer futures as a consequence of continued urbanization and global-scale climate change, and health needs related to heat may grow independently of projected warming as urban populations grow and age (McCarthy et al., 2010). Heat already ranks as a leading weather-related cause of human mortality and morbidity in the US (Berko et al., 2014), and improved planning, preparedness, and response strategies are required now and into the coming decades.

The immediate impacts of heat on human health and well-being span a wide range of events and outcomes, including thermal discomfort, fatigue and exhaustion, cardiovascular and respiratory distress, and heat stroke. Beyond these immediate effects, heat has the potential to disrupt other health-promoting activities. In some regions, heat may deter or constrain outdoor physical activity (Obradovich and Fowler, 2017; Zivin and Neidell, 2014), which has been widely linked to physical (Sallis et al., 1998) and mental health benefits (Frumkin et al., 2017). Furthermore, if heat affects how and where people choose to spend their time, downstream impacts on public transportation, tourism, commerce, and other sectors could occur. Thus, there should be wide interest in understanding more precisely the nature of people's experiences with heat in cities, not only to reduce adverse health events, but also to help cities achieve other goals related to economic growth, efficiency, equity, and overall quality of life.

Vulnerability to heat and other hazards is often defined as a function of exposure, sensitivity, and adaptive capacity (Eisenman et al., 2016;

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Turner et al., 2003). Regardless of the specific framing used to define risk or vulnerability, *exposure* is a critical link in the causal pathway that connects environmental heat to societal outcomes of interest. At the population scale, there have been significant advances over the past several decades in understanding how weather conditions contribute to mortality and morbidity in cities (Anderson and Bell, 2009; Eisenman et al., 2016; Gasparrini et al., 2015; Saha et al., 2013). The repeated identification of temperature-mortality and temperature-morbidity associations across the world points to the obvious importance of exposure. Previous literature has widely established the link between lower socioeconomic status and increased risk of negative heat-related health outcomes (Eisenman et al., 2016; Harlan et al., 2013; Pickett and Pearl, 2001; Reid et al., 2009; Uejio et al., 2011). Characteristics such as higher rates of pre-existing health conditions, lower quality housing, less access to cooling resources, and low surrounding vegetation are common determinants of increased risk. Individuals living in poverty have higher rates of pre-existing health conditions (Joseph et al., 2007; Phelan et al., 2010) and decreased ability to access necessary medical care or cooling resources (Balbus and Malina, 2009), leading to increased risk (Kovats and Hajat, 2008). However, the specifics of population heat exposure—necessitating contact between individuals and the environment—has rarely been considered in heat-health risk assessments as it has been in other environmental topics such as pollution exposure (Ott, 1985). Understanding the circumstances by which people are exposed to heat and how this exposure varies at scales ranging from person-to-person to city-to-city may offer new insights into the risk mitigation and adaptation strategies that might be most efficient or beneficial.

Assessment of heat exposure at the individual level can be difficult, and consequently much research focuses on place-based rather than person-based assessments. Personal heat exposure is defined as contact between an individual and an indoor or outdoor environment that poses a risk of thermal discomfort and/or an increase in core body temperature (Kuras et al., 2017). Thus, assessment of personal heat exposure requires not only information about environmental conditions, but also information about people and their time-activity patterns. Although observational and simulation data related to human time-activity patterns are at the core of exposure assessment for other hazards such as air pollutants (Jerrett et al., 2005; Park and Kwan, 2017), such data have infrequently been collected or examined to understand the nature of health risks associated with heat. The research that does exist spans case study approaches using wearable sensors (Bernhard et al., 2015; Kuras et al., 2015); city-scale assessments using simulation tools (Glass et al., 2015; Karner et al., 2015; Swarup et al., 2017), and analysis of national-scale survey data (Obradovich and Fowler, 2017; Zivin and Neidell, 2014). In addition to heat exposure, activity intensity can also influence heat stress; higher physical exertion (i.e. increased metabolic rates) can accelerate heat exhaustion (Armstrong et al., 2007; Havenith et al., 1998). However, heat exposure research lacks quantification of the intensity of physical activity during hot weather despite clear guidelines to avoid high intensity physical activity when heat stress is possible (OSHA, 2017). As a result, there is opportunity to evaluate activity intensity alongside heat exposure to identify if activity intensity is an overlooked factor when evaluating heat exposure.

To address these research gaps, we focus on two main research questions: 1) How does human activity lead to different levels of outdoor heat exposure in the US urban population? and, 2) How does accumulated heat exposure vary amongst population subgroups in US urban areas?

2. Methodology

To evaluate the relationship of heat exposure with activity, urban location, and demography across the contiguous US, individual-level time-activity data from the American Time Use Survey (ATUS, years 2004–2015) are combined with weather data for major metropolitan statistical areas (MSAs) in the US. Heat exposure during activities is assessed using measures of metabolic intensity, activity duration, and regional apparent temperature.

2.1. Activity data

Administered by the Bureau of Labor Statistics (BLS), the ATUS is an annual and ongoing survey that estimates national trends in labor, health, and social activity. Time use data from the ATUS are compiled to identify historical activity patterns in the urban US Individuals age 15 or older are eligible, and questions are asked via computer-assisted telephone interviewing about time use, socioeconomic status, and characteristics of their household (BLS and US Census Bureau, 2016). The survey of respondent's time use encompasses all activities during a pre-determined 24-h date. We choose the ATUS to evaluate individual heat exposure because it comprehensively documents daily personal time use over a long period for many individuals living in different cities. Activity records are temporally explicit, allowing regional temperatures to be matched with each activity to estimate heat exposure for activities that occur outdoors. We focus on aggregation of ATUS records at the MSA level to compare regional patterns in exposure. This is the smallest spatial scale at which sufficient sample sizes exist for a multi-city analysis, allowing for comparisons across activity times and types, demographic groups, and MSAs. The ATUS has been conducted since 2003, but data utilized is from July 2004 to December 2015 due to significant changes in the survey in mid-2004.

To identify geographic locations of activities, ATUS records are matched to records from the Current Population Survey (CPS) to identify the corresponding MSA of residence for each household (Flood et al., 2015). We choose 50 of the most populous MSAs for evaluation such that a high sample of outdoor activities during hot weather across multiple climates could be assessed. Supplementary Information (SI) Tables S1 and S2 summarize the MSAs included, and Fig. 1 displays a US map with climate zone classifications and MSAs locations. We group MSAs according to the US Department of Energy climate zone classifications (Baecheler et al., 2010) to compare urban heat exposure patterns across contiguous US climates. As this classification system is at the county level, we aggregate up to the MSA level. Of the MSAs in this analysis, 12 have inter-county, intra-MSA climate zone classifications. In these cases, the dominant climate zone by population cover is chosen (see SI Table S3 for details).

2.2. Classifying outdoor activities

This analysis focuses on outdoor activity and its associated heat exposure and metabolic intensity. ATUS activity types and location codes were reviewed to determine which activities occur indoors, outdoors, or at an unknown location, following a similar approach to Zivin and Neidell (2014). As this classification scheme is conservative with marking activities as occurring outdoors, actual time spent outdoors by ATUS respondents may be underestimated.

Activities (ATUS variable TRCODEP) are coded as occurring outdoors or elsewhere (inside or unknown) based on the activity description. Activities are coded as occurring indoors or outdoors if they are explicitly described as such or are highly probable to occur indoors ($P_{indoor} \gg P_{outdoor}$) or outdoors ($P_{indoor} \ll P_{outdoor}$). Note that probabilities for these activities to occur indoors or outdoors are not explicit but used as examples for context. For activities that usually occur indoors but may occur outdoors depending on circumstance ($P_{indoor} > P_{outdoor}$), a classification of 'indoors' is chosen. For remaining cases, such as activities that could reasonably occur either indoors or outdoors ($P_{indoor} \cong P_{outdoor}$), or locations with vague descriptions, a classification of unknown is chosen. The distinction between indoor activities and activities with an unknown location is trivial for this analysis because only outdoor heat exposure is being investigated, but indoor and unknown activity locations are still differentiated for clarity. Examples of