Health & Place 43 (2017) 85–94

Contents lists available at ScienceDirect

Health & Place

journal homepage: www.elsevier.com/locate/healthplace

Individual exposure estimates may be erroneous when spatiotemporal variability of air pollution and human mobility are ignored

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ARTICLE INFO

Keywords:
Environmental health
Air pollution exposure
Human mobility
The uncertain geographic context problem (UGCoP)
3D geovisualization

ABSTRACT

This study aims to empirically demonstrate the necessity to consider both the spatiotemporal variability of air pollution and individual daily movement patterns in exposure and health risk assessment. It compares four different types of exposure estimates generated by using (1) individual movement data and hourly air pollution concentrations; (2) individual movement data and daily average air pollution data; (3) residential location and hourly pollution levels; and (4) residential location and daily average pollution data. These four estimates are significantly different, which supports the argument that ignoring the spatiotemporal variability of environmental risk factors and human mobility may lead to misleading results in exposure assessment. Additionally, three-dimensional (3D) geovisualization presented in the paper shows how person-specific space-time context is generated by the interactions between air pollution and an individual, and how the different individualized contexts place individuals at different levels of health risk.

1. Introduction

Air pollution can lead to a variety of health problems, such as respiratory and cardiovascular issues, lung cancer, and even premature death. The American Lung Association reports that ground-level ozone is the most widespread pollutant in the U.S., and it is especially harmful to children, the elderly, people with cardiovascular or lung diseases, and people who work outdoors. To better assess the adverse health effects of ozone on humans, it is important to estimate personal exposure more accurately. Given that the level of air pollution is continuously changing over space and time and that humans are mobile across space, both of these dynamic characteristics and their complex interactions should be considered in order to accurately assess personal exposure levels (Buonanno et al., 2014; Dons et al., 2011; Fang and Lu, 2012; Kwan et al., 2015; Lu and Fang, 2015; Pilla and Broderick, 2015; Ryan et al., 2015; Steinle et al., 2013, 2015; Yoo et al., 2015; Zhou et al., 2011).

However, many previous environmental health/exposure studies tended to assume that air pollution levels are spatially stationary and temporally constant throughout a day, month, or year or that people are non-mobile and thus are not exposed to air pollution in areas outside of their residential neighborhoods. For example, one study used a ten-year geometric mean concentration of ambient air pollution and census-tract level socioeconomic and demographic data (Jerrett et al., 2001). Similarly, Gray et al. (2013) utilized daily average particulate matter ($PM_{2.5}$) concentrations, daily eight-hour maximum ozone concentrations, and census-tract level demographic data. In Buzzelli and Jerrett (2007)'s study, the two-week average of nitrogen dioxide (NO_2) concentrations in Toronto was used together with Statistics Canada's 2001 census data to obtain the socioeconomic status of places of residence. Some other studies attempted to take human mobility and non-residential exposures into account (Chum and O'Campo, 2013; Nyhan et al., 2016; Setton et al., 2008). However, these studies also used temporally aggregated air pollution data (the average weekday 24-h traffic volume data as a proxy for air pollution; daily $PM_{2.5}$ concentrations; and the annual average NO_2 concentrations, respectively).

While these previous studies offer a useful foundation for future research, they have several limitations. First, because air pollution levels not only change across space but also change between hours or even minutes, it is important to consider their spatiotemporal variations and the dynamic interactions between pollutants and humans at fine spatiotemporal scales (Yoo et al., 2015). In reality, people are not affected by the "average" pollution level but by specific hourly pollution levels during a day, which can directly cause acute symptoms (e.g., acute asthma). Therefore, hourly air pollution concentrations seem more relevant to vulnerable people than merely the daily or monthly average, because finer temporal information would enable them to change their daily space-time behaviors to minimize exposure.

Second, it has been noted that personal or individual exposure to

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http://dx.doi.org/10.1016/j.healthplace.2016.10.002
Received 25 February 2016; Received in revised form 21 September 2016; Accepted 16 October 2016
Available online 30 November 2016
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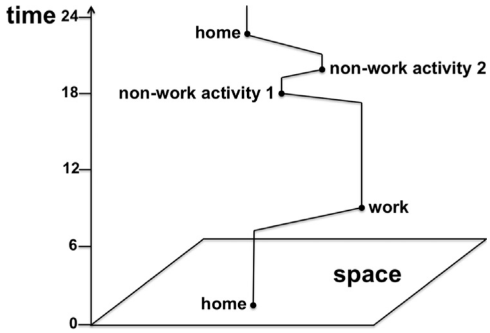

Fig. 1. An individual's daily movement trajectory can be represented as a continuous temporal sequence from the time-geographic perspective. Time geography was originally developed by Hägerstrand (1970), and it provides a useful framework for examining the complex interaction between human movement and environmental stressors in space-time.

environmental influences is determined both by a person's specific location and how much time the person spends there when undertaking daily activities––such as work, grocery shopping, and other non-work activities (see Fig. 1)––rather than being determined solely by the person's residential area (Crawford et al., 2014; de Nazelle et al., 2013; Kwan, 2009, 2012a; Kwan et al., 2015; Setton et al., 2011; Yoo et al., 2015). This means that *where people live* is often not the only important factor in determining their exposure to environmental factors. Rather, *where people visit* and *how much time they spend at a particular location* are more relevant to assessing the effects of environmental factors on people's health behaviors or outcomes. Since most previous studies did not take into account the variety of places that people visit on a daily basis (Hernandez et al., 2015), they did not capture the full range of personal exposure at various locations and moments.

These two underlying assumptions often found in previous environmental health studies may lead to considerable uncertainty in research results, as part of the uncertain geographic context problem (UGCoP) (Kwan, 2012a,b) that has recently been articulated. The UGCoP refers to the issue that research conclusions about the effects of environmental influences on a person's health are sensitive to different delineations of the geographic and temporal contexts used to derive the relevant environmental variables. This problem arises when data are aggregated over areas (e.g., census tracts) that do not necessarily correspond to where people actually visit in their daily lives and have a coarse temporal resolution, because such data contain uncertainties in the relevant spatiotemporal contexts in which an individual is exposed to environmental influences, such as air pollution (Kwan, 2012a). As a result, findings from studies that are based on either of these two assumptions may be inaccurate or even entail a significant inferential error.

Since the UGCoP may contribute to misleading findings in studies on environmental (or contextual) effects on people's health behaviors or outcomes (Chen and Kwan, 2015; Kwan, 2012a), some recent studies have begun to pay attention to the UGCoP as a fundamental methodological issue and recognized the need for mitigating its effects on research findings (Liao et al., 2014; Park and Kim, 2014; Robinson and Oreskovic, 2013; Weaver, 2014). Using detailed individual movement data containing accurate spatial and temporal information can mitigate this problem because the data help to delineate the individualized space-time context in which a person is actually affected by relevant environmental or neighborhood factors (Kwan, 2012a,b). In addition, if a relevant environmental factor (i.e., air pollution) continuously changes over space and time at a fine scale, considering the fine spatiotemporal variation of the factor within the individualized space-time context significantly contributes to mitigating the UGCoP as well.

Despite its importance, however, most environmental health studies to date have paid little attention to the confounding effects of the UGCoP, especially in empirical research on air pollution exposure and its health effects. This may be due to the limited availability of public data, the cost and time for collecting high-resolution data, privacy and data confidentiality issues, and computational complexities (Kwan, 2012b). However, issues regarding personal privacy and cost in this kind of research can be addressed with suitable protective human subjects protocols and adequate funding support. As an alternative, researchers may conduct simulations to create realistic individual-level data based on aggregate data that are widely and publicly available (which is known as "down-scaling" in spatial analysis, and the technique has received increasing attention recently). In addition, recent advances in geographic information science (GIS), geospatial technologies, and geographic masking methods for privacy protection have also helped to address some of these issues (Kwan et al., 2004; Kwan and Schuurman, 2004; Kwan, 2012b). Mobile tracking and sensing technologies (e.g., global positioning systems [GPS] and portable air pollution sensors) have increasingly been used to collect accurate high-resolution data about individual movement and personal exposure to air pollution, which in turn may help address the UGCoP.

As an example of studies using such technology, Lu and Fang (2015) used a GPS-equipped mobile air sensor to collect air pollution levels in a single person's immediate surroundings and presented the movement trajectory using a space-time cube. The mobile sensor enabled them to simultaneously consider real-time air pollution concentrations and human movement patterns. However, because the study used only one person's data, it did not provide adequate empirical evidence for evaluating the argument that multiple people living in the same residential area can experience significantly different exposure levels if they have different movement patterns. Further, although the study visualized a single movement trajectory that was color-coded based on the values of the air quality index, the geovisualization did not include spatiotemporally varying air pollution prediction surfaces simultaneously. Therefore, it is difficult to discern at a glance how the complex interactions between constantly changing spatiotemporal contexts (i.e., the space-time patterns of air pollution) and human movements lead to various exposure levels and potential health effects.

In this study, using geospatial methods and three-dimensional (3D) geovisualization, we aim to empirically demonstrate why including *both* the spatiotemporal dynamics of air pollution and human movement is important in environmental exposure (or health risk) assessments. We argue that the two common assumptions often used in past studies may lead to a considerable inferential error or misleading findings due to the UGCoP. To support this argument, this study compares four different types of exposure estimates generated using four types of data: Simulated individual-level movement patterns, individuals' residential locations, hourly air pollution levels, and daily average pollution levels. In addition, this study uses 3D geovisualization to illustrate how air pollution levels are spatiotemporally dynamic, how people move around during a day, and how potential health effects may vary depending on both of these dynamic patterns during a day. Although this study focuses on Los Angeles County in California, the methods used in the study are also applicable to other cities (in the U.S. or in other countries, such as Canada, Europe, and Asia) where air pollution is a serious health hazard.

2. Data and methods

2.1. Study area

Los Angeles (LA) County in California, the study area, is well known for having air pollution in the form of smog, which mainly consists of ozone (Gorai et al., 2015). The American Lung Association reports that the Los Angeles-Long Beach metropolitan area in California ranks first for high ozone days among the 277 metropolitan areas in the U.S. The

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