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Advances in portable sensing for urban environments: Understanding cities from a mobility perspective

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ABSTRACT

Portable sensing, in which lightweight mobile sensors are used to measure stimuli, events, and human behavior, is a new and disruptive data collection paradigm. It has several methodological advantages compared to traditional methods and is suitable for investigating the dynamism of increasingly mobile and urban societies. In this article, we discuss the motivations behind the use of portable sensing and reflect upon the advances, limitations, and future of the field. Although portable sensing is still in its infancy, we foresee that its utilization will grow in the coming years. For portable sensing to become a prevalent and legitimate methodological approach, it is essential to have conceptually strong study designs that are grounded in suitable ethical procedures and comply with data protection regulations.

1. Background

Portable sensors are lightweight devices that can respond to physical stimuli or events and log or transmit their readings to other electronic devices. They are usually compact, have low power consumption, and are capable of wireless communication with other devices. These properties make them easy to transport by humans or vehicles and to operate while on the move. In this article, we refer to portable sensing in the broadest sense, including any information that can be gauged about the status of an event or a stimulus through an electronic device. This includes smart cards that embed radio-frequency identification (RFID) technology (see, Zhang, Sari Aslam, Lai, & Cheng, 2020 in this special issue), as well as people who report their affective status or their immediate environment through their smartphones using repeat frequent surveys (also known as ecological momentary assessment) (Birenboim & Shoval, 2016; Helbich, 2018; Kou, Tao, Kwan, & Chai, 2020).

Such portable devices are not entirely new, but their usage has been surging in recent years due to technological developments. In this special issue, we introduce the motivations behind the use of portable sensing technology in urban and environmental research, as well as its practical use, future potential, and limitations. This is done through five articles that cover broad types of technologies across different environmental and urban research domains. While portable sensing has yet to become a common data collection tool, we foresee that it will mature into a central tool in future investigations of urban environments.

2. Why use portable devices?

2.1. The mobility turn and acceleration of social processes

In their seminal work on the new mobilities paradigm, Sheller and Urry (2006) argue that mobility is becoming an increasingly important phenomenon. They call for a new research perspective that takes mobility as a main research subject that shapes our world and society. The mobility turn, as they call it, is reflected in the rapid increase in the movement of people, commodities, resources, information, and images.

Related to Sheller and Urry's notion of the mobility turn, scholars have indicated that the pace of life has accelerated in late modern societies (Wajcman, 2008). This means that people do more and experience more in less time (Rosa, 2003). Such an accelerated environment generates a dynamic existence in which individuals rapidly move from one occurrence to the next and in which one experience follows the other. The social trends that are reflected in such theoretical approaches call for a new and more dynamic investigation of daily lives. In this sense, portable sensing that enables the recording of data continuously during people's daily routines when they are mobile is an attractive

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methodological option, as it allows researchers to investigate our current dynamic societies, individuals, and things.

Kwan (2018a) further argues that using a static perspective on the geographical context is problematic. Ignoring people's daily mobility may not only lead to erroneous assessments of individuals' exposure levels, as discussed below, but also have significant social implications, because considering people's mobility allows us to obtain a more nuanced understanding of their daily practices and experiences: For example, how residents of disadvantaged neighborhoods may mitigate some neighborhood stressors through their daily mobility; how some residents are more exposed to local stressors due to their immobility; and so on (Kim & Kwan, 2021). In this sense, a portable sensing paradigm is essential to understand how people adopt mobility practices in their lives in increasingly mobile societies.

2.2. Technological opportunities and availability

Advances in ambulatory or portable sensing would not have been possible without recent technological developments. In particular, sensors have become smaller, more power efficient, and more reliable, and have greater connectivity to other devices. In order to enrich sensor data on various environmental contexts that are obtained from portable devices, it is necessary to continuously record the device's geographical location (Estrin, Girod, Pottie, & Srivastava, 2001). The advancement and growing availability of location tracking technologies such as the global positioning system (GPS), especially since the 2000s, have therefore been fundamental to the ability to implement portable sensing in urban, environmental, and geographical research.

Another key factor that further supports the attractiveness of portable sensing devices to research relates to their rapid popularization. First and foremost, it is the smartphone that has revolutionized the field (Birenboim & Shoval, 2016). Since the launch of the first iPhone in 2007, smartphones have been rapidly adopted by the general population. In developed countries, the vast majority of the population now own smartphones and developing countries show a rapid increase in ownership, especially among younger people (Pew Research Center, 2019). This means that the majority of adult people in the world are now able to continuously log and transmit sensor data through their phones, and this practice has come to be known as mobile sensing (Chaix, 2018). Current smartphones have an extensive set of sensors that are frequently upgraded by their manufacturers. Even many low-end smartphones include an impressive number of sensor technologies, such as an accelerometer, several location technologies, a microphone that records sound, a camera, an ambient light sensor, a proximity sensor, and a magnetometer. Additional useful sensors such as a barometer, ambient temperature and humidity sensors, and even a pedometer and heart rate sensors can be found in some higher-end devices. Moreover, smartphones allow users to act as "human sensors" and to send structured and non-structured data and reports.

Though not as common as smartphones, smart watches and smart bands are another popular portable technology that is equipped with sensors. As many of these devices are used to monitor health and fitness activity, they include sensors such as a heart rate monitor, an oximeter (blood oxygen sensor), and a pedometer (Birenboim, Dijst, Scheepers, Poelman, & Helbich, 2019; Nelson et al., 2020) alongside more conventional sensors that can also be found in basic smartphones. Smart watches and bands are gaining popularity as part of "quantified self" practices (Swan, 2013) and thanks to the improvement in the sensors' quality, their clinical potential is starting to be acknowledged (Tison et al., 2018). Smartwatches are part of a larger family of wearable sensor devices that includes items such as rings, socks, shirts, and glasses that can be used to monitor physiological signals and mobility, and in some cases also parameters of the ambient environment.

Portable sensors that are not carried by people have also greatly increased in number and variety and significantly improved in quality. This is associated with the "smartization" processes that society is now undergoing in which, among other things, sensor technology is being integrated into many everyday devices and infrastructures. These sensors are often connected to the internet (Internet of Things) and can transmit information that can be analyzed in real-time and supply invaluable information concerning the status of the device, infrastructure, and/or ambient environment (Perera, Zaslavsky, Christen, & Georgakopoulos, 2014). Sensors that are incorporated into "things" are becoming one of the major sources of sensor data. In some cases, these sensor devices are portable, allowing data collection on the move. A notable example is the incorporation of sensor technology in autonomous vehicles (Campbell et al., 2018) and uncrewed aircraft (Jacob, Chilson, Houston, & Smith, 2018). Following these trends, we should expect even greater availability of mobile sensor data in the years to come.

Finally, other more niche sensors are becoming increasingly available. Such sensors include devices that monitor parameters of the ambient environment (e.g., air quality, noise) (Ma, Rao, Kwan, & Chai, 2020; Schnell, Cohen, Mandelmilch, & Potchter, 2021 in this special issue; Zhang, Zhou, Kwan, Su, & Lu, 2020) and more unique physiological sensors such as mobile electroencephalograms to capture brain activity data while moving through a city (Aspinall, Mavros, Coyne, & Roe, 2015; Lin et al., 2020; Mavros, Austwick, & Smith, 2016). These types of sensors are not likely to be adopted by the masses, but they are becoming increasingly more affordable and more user-friendly, which makes their implementation in research more feasible. Some of these sensors might be integrated with other devices, some of which are mentioned above (i.e., smartphones, wearables, "everyday devices" sensors).

2.3. Methodological advantages

Portable sensors have several technical capabilities and qualities that could be methodologically advantageous. (1) *High temporal granularity* – similar to other sensors, many portable sensors can record information in high temporal resolutions of, in some cases, parts of seconds. When combined with accurate location readings (i.e., through location tracking technologies), portable devices may generate information with a very precise spatiotemporal stamp. (2) In situ *data collection* – being portable means that the sensors can be carried across space and allow the measuring of data in the exact place where events take place and where participants perform their activities. (3) *Continuous data collection* – many sensors can work continuously and record data passively without any human intervention (occasionally referred to as opportunistic sensing). (4) *Objective measurements* – data collected by sensors is objective in nature, though this does not necessarily mean that sensor data are always more reliable than or superior to other, self-reported data collection methods. However, taking sensor measurements longitudinally at very frequent intervals eliminates people's response fatigue (i.e., the tiredness that respondents experience as a result of answering survey items, which leads to a deterioration in data quality).

The combination of these technical qualities has several methodological benefits. Here, we emphasize three such interrelated potential advantages by contrasting the portable sensing approach with other more traditional data sources and data collection techniques, namely the analysis of aggregative census-tract-level data, traditional self-reported questionnaires, lab experiments, and the usage of stationary sensors.

2.3.1. Overcoming methodological concerns regarding the environmental context

Portable or mobile sensing allows researchers to mitigate at least three major methodological problems related to the delineation of the environmental context and the assessment of the impacts of environmental factors on human behaviors and outcomes (Helbich, 2018). The first is the uncertain geographic context problem, which is a result of using predefined and arbitrary geographical units (e.g., districts, census tracts, neighborhoods, buffers around the home) as areas for capturing the contextual influences of environmental factors (Kwan, 2012, 2018b). The uncertain geographic context refers to the problem that findings about the effects of area-based attributes (e.g., land-use mix) on individual behaviors or outcomes (e.g., physical activity) could be affected by how contextual units or neighborhoods are geographically delineated. Another aspect of the uncertain geographic context problem arises from the reliance on sparse stationary monitoring stations to infer individual exposure to environmental factors such as air quality, noise, and ambient air temperature that people experience in their daily lives (Kwan, 2013; Ma et al., 2020). This approach ignores the high spatial and temporal variability of environmental factors and the variations in exposure levels as people move around in their daily lives and are exposed to different environmental contexts (Roberts & Helbich, 2021).

Second, the aggregation and organization of data in predefined geographical units has become common practice due to the high availability of data resulting from administrative enumeration units like census tracts. This has restricted researchers to performing their analyses at census-tract or other fixed-scale units and may lead to the widely known modifiable areal unit problem. The third methodological problem is the neighborhood effect averaging problem, which is a result of considering the home neighborhood as the sole environmental context and disregarding people's daily mobility when assessing mobility-dependent exposures like air pollution and noise (Kwan, 2018a). The neighborhood effect averaging problem reflects that individual mobility-based exposures to environmental factors tend towards the mean level of the participants or population of a study area when compared to their residence-based exposures. As a result, ignoring people's daily mobility and exposures to nonresidential contexts in geographic or epidemiological studies may lead to erroneous results in the study of mobility-dependent exposures (e.g., noise and air pollution) and their health impact (Kim & Kwan, 2021).

Portable sensing may mitigate these methodological problems (Park & Kwan, 2017; Schnell et al., 2021 in this special issue) and even enhance the quality of the data. In the field of environmental health, it has been suggested that dynamic approaches focusing on the duration, sequence, and accumulation of exposures reduce exposure misclassification problems (Helbich, 2018), while allowing longer periods of exposure monitoring (Loh et al., 2017). Furthermore, it allows researchers to investigate the effect of the urban environment at the micro-level (i.e., the effect of the immediate environment) (Birenboim, 2018; Millar et al., 2021 in this special issue; Su, Zhou, Kwan, Chai, & Zhang, 2021).

2.3.2. Ecological validity

The ability of portable sensors to continuously collect in situ data allows researchers to study behavior in naturally occurring environments and therefore improve the ecological validity of the study (i.e., the extent to which results resemble and can be used to infer real-world situations). The importance of ecological validity has been increasingly emphasized in behavioral sciences, initiating a search for suitable methods and tools (including sensors) that allow studies to be conducted outside well-controlled lab environments and in real-world settings (Fahrenberg, Myrtek, Pawlik, & Perrez, 2007; Ladouce, Donaldson, Dudchenko, & Ietswaart, 2017).

2.3.3. Coverage and resolution

Portable sensors that are dynamically spread throughout a city may increase the spatial distribution of samples (compared to sparsely distributed stationary monitoring stations) and hence increase the spatial resolution of data (Apte et al., 2017; Yin et al., 2020 this special issue). However, when there are too few portable sensors (which is often the case), sample coverage is most likely to be insufficient to give a reliable picture of dynamic environmental phenomena (e.g., spatial coverage will not be complete and/or the temporal resolution of the data will be limited). Successful examples of measuring dynamic changes in environmental conditions include road traffic measurement through mobile applications. The ability to supply good spatial coverage through portable sensors is dependent on the availability of sensors that are cost-effective, easy to carry, and used on a daily basis (Loh et al., 2017). In cases where temporal resolution is less critical (e.g., when mapping the condition of the road network in a city, Eriksson et al., 2008), even a small number of sensors may be sufficient to map environmental properties of a large area at high spatial resolution.

3. Ways in which portable sensing devices can be incorporated in studies

There are several ways in which researchers can employ portable sensors. Using a series of dichotomic properties, this section characterizes the practices of portable sensor usage. Importantly, the components of each pair should be seen as complementary rather than alternatives to one another and they can often be used simultaneously in a study.

3.1. Sensing environments vs. sensing agents

Portable sensing devices can be used to collect data on the agent—be it a human or an object (e.g., car)—that carries them (e.g., position, physical status) and/or on the adjacent environment (e.g., ambient temperature, noise). In many cases, researchers are interested in data on both the agent and the environment, since the combination of the two allows them to infer the status of the agent in relation to a specific environment. In some cases, the same sensor can be used to record data on both the agent and the environment. For example, an accelerometer can be used to record not only the intensity of physical activity of the agent, but also the condition of the environment (e.g., identify road potholes) (Eriksson et al., 2008)

3.2. Traditional research vs. mobile crowdsensing

Mobile crowdsensing is a "sensing paradigm [closely related to participatory sensing (Burke et al., 2006)] that empowers ordinary citizens to contribute data sensed or generated from their mobile devices, aggregates and fuses the data in the cloud for crowd intelligence extraction and people-centric service delivery" (Guo, Yu, Zhou, & Zhang, 2014, p. 593). It allows gathering data from mobile phone users both explicitly and implicitly. The main advantage of this approach lies in its ability to collect massive amounts of data at relatively low costs. However, compared to traditional research designs it has several disadvantages that should be considered. For example, data can often be of low quality, participants' background and characteristics are not always known, and the sample is likely to be biased. These issues should be considered when deciding on the methods and tools to be used, especially when the study focuses on human behavior.

3.3. Participatory vs. opportunistic

Two types of sensing approaches are associated with smartphone sensing (and are also applicable to other sensor devices), namely participatory (to be distinguished from participatory sensing in Section 3.2) and opportunistic (Birenboim & Shoval, 2016; Lane, Eisenman, Musolesi, Miluzzo, & Campbell, 2008). The former requires users to be actively involved (e.g., take a picture, respond to a survey) and is therefore highly dependent on users' enthusiasm. In the latter case, sensing is reliant on background processes that automatically log sensor (e.g., GPS, barometer) and phone usage data (e.g., call records, Wi-Fi usage, Bluetooth devices in the vicinity). Since opportunistic sensing does not require any input from participants and subjects do not need to carry or wear additional devices (doing so may affect their behavior), it allows longer sensing periods and unintrusive, more systematic data collection with high temporal resolution.

3.4. Dedicated devices and applications vs. using existing devices and applications

Portable sensing can be performed using existing hardware and software (e.g., mobile phones that collect location data for non-research purposes) or through dedicated devices that are designed for specific research purposes (e.g., air quality sensors). There will often be a tradeoff between the costs of using the outputs of the device and the quality of the data. When relying on existing sensor data, researchers might not get the optimal data they require for their investigation, but costs will usually be lower. In contrast, when using dedicated devices, researchers can control the type and quality of the device and data, the sampling frequency, the sample characteristics, etc. In this case, however, the costs of the hardware and the data collection procedure (e.g., recruiting participants and distributing the sensors) will usually be greater.

3.5. Sensors only vs. sensors as a complementary tool

Researchers may decide to use portable sensing as a standalone method or as a complementary tool. The decision on this issue is dependent on the epistemological presuppositions of the researcher. Some might find sensors highly systematic, objective, and valid tools that are sufficient as data collection tools by themselves. In contrast, some might consider sensors as limited tools that, at best, only reflect symptoms of a phenomenon and, therefore, they can only be used as a supporting tool that reconfirms other findings. For example, Resch, Puetz, Bluemke, Kyriakou, and Miksch (2020) made use of biosensors to record physiological information combined with eDiary, first-person perspective videos, interviews, and surveys to depict the emotional state of participants. Further, the "objective" environment (e.g., noise levels) as measured by portable sensors may not have a consistent relationship with people's perceived exposures to the objectively measured environment and its impacts on their health and wellbeing (Kou et al., 2020). It is thus important to also take into account people's subjective experiences when undertaking research using portable sensors.

4. The limitations and future of portable sensing

4.1. The limitations of portable sensing

While the implementation of portable sensing techniques is promising, researchers should keep in mind the current limitations of these techniques. One of the main limitations is their inferior quality (Thompson, 2016). Compared to static sensors (e.g., those installed at environmental monitoring stations), portable sensors tend to be less accurate and reliable due to technological constraints posed by their size and limited power availability (i.e., they are often dependent on battery power). Moreover, they are often located in suboptimal positions (e.g., electrodermal activity sensors are often located on the wrist rather than on the palm; Birenboim et al., 2019). Nevertheless, in some cases portable devices may compensate for their inferior accuracy by allowing larger sample sizes and covering larger areas.

Second, as the method and the sensors themselves are rather new, there is not always a gold standard for the quality of sensors and the sampling procedure. In these situations, researchers are required to validate the sensors and, in some cases, devise new data collection procedures. However, it can be expected that, as time goes by, common standards and methods will gradually emerge. Third, as there is usually no off-the-shelf software that integrates and analyzes sensor data, data analysis is still not straightforward. Fourth, some of the sensors are still relatively expensive (though usually cheaper than static sensors) and data collection procedures are often resource-demanding and time-consuming when using dedicated devices. This reduces the ability to perform large-scale studies.

4.2. The future of portable sensing

Portable sensing is still in its early stages of adoption. Most studies that utilize this data collection paradigm are focused on presenting a proof of concept or discussing methodological issues, and they tend to rely on limited samples. Prominent research fields that have already started to utilize this approach more substantially in an urban context include environmental health and health geography research in which the level of individual exposure to physical and social environmental factors and their impact on people's physical and mental health and wellbeing is measured at high resolutions (Kou et al., 2020; Kwan et al., 2019; Roberts & Helbich, 2021; Zhang, Zhou, et al., 2020); urban and transportation management and planning (Long & Reuschke, 2021; and Millar et al., 2021 in this special issue); and health monitoring including measuring mobility, physical activity, and physiological status (Li et al., 2017). The study of urban subjective experiences and emotions using portable sensors is another field that has emerged in recent years (Birenboim, 2018; Osborne & Jones, 2017; Shoval, Schvimer, & Tamir, 2018).

For portable sensors to become more prevalent in future studies, several challenges need to be addressed. First, the data produced by portable sensors in many cases requires improvement. This could be done through both hardware and data processing improvements (i.e., using post-processing procedures that improve data quality). Fortunately, it seems that due to the growing demand for various types of portable sensors, the quality of data will improve in the coming years. Another way to improve data quality is to rely on multiple data sources, namely remote sensing and various static and portable sensors. These data sources can be used to model the environment in high spatiotemporal resolutions (see, for example, Yin et al., 2020, in this special issue). Second, data collection and analysis procedures should be standardized to allow simple implementation and reduce the barriers to implementation for researchers. The utilization of portable sensing for urban analysis beyond pilot studies may require larger samples compared to well-controlled lab experiments. We therefore advocate the development of conceptually strong observational study designs and frameworks that are well adjusted and based on repeated measurements. Third, and of utmost importance, critical ethical and privacy issues should be addressed. In particular, portable sensors that include location information arouse privacy concerns, which are likely to increase when less conventional data sources, such as crowdsourced data, are used. In these cases, data collection is not always controlled, participants do not sign informed consent forms, and they are not aware of how their data is being used. Advancements in portable sensing should therefore be accompanied by suitable ethical procedures that comply with the latest data protection regulations.

As a final note, the implementation of portable sensors should be carefully thought through. One should consider the advantages of the technology compared with more traditional methods. It is not always the case that portable sensing will be superior to more traditional methods, especially at the current stage of portable sensing. Nevertheless, we believe that with the growing availability and improved quality of sensors in the coming years, portable sensing techniques will become a legitimate and central source of data. As discussed in this introduction and demonstrated by the articles in this special issue, portable sensors hold great potential for researchers who study our dynamic cities.

Declarations of interest

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