Mobile Phones as Ubiquitous Social and Environmental Geo-Sensors

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INTRODUCTION

Mobile communication networks have been designed to allow people to communicate wirelessly almost everywhere at all times. Particularly in urban environments such networks are ubiquitous, and so are the mobile communication services they offer. Moreover, communication networks can be seen as higher-level large-scale human behavior sensors (Shoval, 2007), which include in fact hundreds of thousands of mobile in situ geo-sensing components, i.e., the mobile phones carried by their users. The term "in situ," in contrast to "remote," means that the sensor is very close to, or in direct contact with the phenomenon being sensed. For instance, measurements from an air temperature sensor are an example of environmental in situ sensor data. Like this, the user-generated traffic within mobile networks, as well as the geo-referenced social media data published by individuals, can serve as a proxy for the collective human behavior. Such user-generated data are referred to as social in situ sensor data (Sagl & Blaschke, 2014).

Today, smartphones are sensor-rich devices, which are increasingly leveraged as ubiquitous mobile sensors (Khan et al., 2013; Lane et al., 2010) that are able to sense their immediate surroundings on site in high spatial and temporal detail. In fact, people themselves can act as human sensors and provide subjective "observations" in the form of individual perceptions. Such perceptions are increasingly shared by people voluntarily as geographic information on diverse Web 2.0 and social media platforms (e.g., geo-tagged pictures and text on Twitter, Instagram, etc.) via their mobile phones and a mobile network. Such human sensor data can complement calibrated electronic sensor measurements from geo-sensor networks, e.g., for environmental monitoring.

The resulting vast volumes of social and environmental in situ sensor data digitally reflect, to some degree, the spatial and temporal dynamics of human behavior and environmental phenomena, for instance large-scale activity and mobility in urban spaces or objective measures or subjective observations of weather conditions. Furthermore, the consolidation of these highly diverse data on a common space-time basis enables further analyses. The results of such analyses can potentially shed new light on local and short-term environment-human interaction aspects, for instance, the relationships between weather conditions and collective human behavior.

In this article, we illustrate the use of mobile phones as ubiquitous social and environmental geo-sensors in order to provide additional insights into the space-time behavior of the underlying geographic phenomena. We focus on investigating human and environmental dynamics, and potential human-environmental relationships. Since such dynamics inherently comprise both a temporal and a geo-spatial component, we herein underpin the added value of integrating interdisciplinary meth-

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ods linked with Geographic Information Science (GIScience) theory and Applied Geoinformatics into the analysis of mobile phone behaivor.

In the following sections we start with providing a brief overview of the intellectual history in that research field including influencing scholars and institutions. In the main part we elaborate on the current scientific knowledge of three concrete research areas: human-centered data acquisition, space-time patterns of human behavior, and relationships of human behavior in the environmental context. Finally, we provide a conclusion and future research directions related to the overarching context of investigating human and environmental dynamics based on diverse human and technical in situ sensor data.

OVERVIEW OF THE INTELLECTUAL HISTORY

In this article, we put emphasis on the geo-spatial and temporal components of mobile phone data acquisition and data analysis. We focus on the following three concrete research areas:

- Human-centered data acquisition using mobile phones;
- Space-time patterns of human behavior derived from mobile phone data;
- Exploring human behavior in the environmental context.

As a result from deficient data availability and the fast rise of smartphone penetration, new human-centered approaches for data acquisition are currently investigated. The interaction with social media such as Twitter, Instagram, Facebook, etc. is increasingly happening on mobile devices (Perreault & Ruths, 2011), thereby generating vast amounts of Volunteered Geographic Information (VGI) (Goodchild, 2009; Goodchild, 2007a). Data from mobile networks and social media thus reflect, to some degree, the dynamics in social environments. Additionally, the concept of "People as Sensors" (Resch, 2013) allows people to share their individual perceptions as subjective "observations" of, e.g., air quality, the weather, or even their situational emotional feeling via their mobile phones (Resch, Summa, Sagle, Zeile, & Exner, 2015). Like this, the gathered observations complement measurements from technical sensor networks. This is also underpinned by Sarah Elwood who discusses societal implications of neogeography and the "geo-spatial web" and tries to define future research avenues through an extensive review of early literature in the field (Elwood, 2008a, 2008b, 2010).

Research in the field of urban social dynamics and human behavior patterns based on mobile phone data has been intensively conducted by the MIT's SENSEable City Lab, Boston (USA), and partner institutions, with several pioneering and currently leading scholars (Calabrese et al., 2013; Calabrese et al., 2011c; Di Lorenzo & Calabrese, 2011; Krings et al., 2009; Quercia, 2010; Ratti et al., 2006; Ratti et al., 2007; Ratti et al., 2010). Recent examples of urban social dynamics and human behavior patterns are shown in Real-Time Rome (Calabrese et al., 2011a) or LIVE Singapore! (Kloeckl et al., 2012). In the domain of formal mathematical modeling, i.e., deriving general laws of human behavior from vast volumes of mobile phone data, the most influencing scholars are, e.g., Barabási (2005), González and Barabási (2007), Onnela et al. (2007), González et al. (2008), Candia et al. (2008), Simini et al. (2012). One important geographic location for that pioneering research is the Center for Complex Network Research (CCNR), Northeastern University, Boston (USA).

Understanding the complex interactions between the environment and humans and the interactions' inherent dynamics is a multidisciplinary challenge. Herein we summarize recent approaches that explore human-environment interactions based on social and environmental sensor data. We focus on the spatial and temporal components of the underlying, typically geographic phenomenon. Since such approaches are rarely documented in scientific literature yet,