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Analysis of pedestrian behaviors through non-invasive Bluetooth monitoring

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ABSTRACT

This paper presents a novel framework to analyze pedestrians' behavioral patterns throughout shopping environments in the historical center of Barcelona, Spain. We employ a Bluetooth detection technique to capture a large-scale dataset of pedestrians' behavior over a one-month period, including during a key sales period. We focused on comparing particular behaviors before, during, and after the discount sales by analyzing this large-scale dataset, which is different but complementary to the conventionally used small-scale samples. Our results uncover pedestrians actively exploring a wider area of the district during a discount period compared to weekdays, giving rise to strong underlying mobility patterns.

1. Introduction

This paper analyzes pedestrians' mobility patterns during a special event, when their behaviors are believed to differ from those during a normal day. We focus on examining behavioral differences between discount days and other normal sale days in the shopping environment, in terms of their paths, consisting of the number of visited nodes, their sequential order, and the length of their stay in the district.

Tracking pedestrians' trajectories in a shopping area has long been identified as a critical research area for urban researchers. Scholars have pursued developing mathematical models of spatial shopping behaviors to predict the relevant impacts on the shopping environment, such as the number of visitors to shops or shopping centres of the city (Rasouli & Timmermans, 2013). Retailers also show their interests in such analysis due to the potential impacts on the turnover of their shops and the real estate values (Borgers & Timmermans, 2005, 2014; Kurose, Borgers, & Timmermans, 2001). Conversely, for the city authorities, such analysis can be used for the prediction of the consequences of urban planning and market shares (i.e., effects of store replacements), and for efficient crowd management (Schadschneider, Klingsch, Klupfel, Kretz, Rogsch & Seyfried, 2009).

In the framework of modeling and analyzing the dynamics of pedestrian behaviors in the shopping environment, research has been conducted to uncover the relationship between pedestrian behaviors and the features of the shopping environment (Borgers & Timmermans, 1986a, 1986b, 2005; Borgers, Kemperman, & Timmermans, 2009; Dijkstra, Timmermans, de Vrie, 2009; Dijkstra, Timmermans, & Jessurun, 2014; Kemperman, Borgers, & Timmermans, 2009; Kurose et al., 2001; Kurose, Deguchi, & Zhao, 2009; Zhu & Timmermans, 2008). The data collection methodologies for those analyses are largely based on paper-and-pencil on-site interviews or questionnaires (see Borgers & Timmermans, 1986a, 1986b, for the detailed survey method). By limiting the survey area, the interviewers intercepted the pedestrians randomly and asked questions about the following: length of stay in the area, taken routes, number and order of visited shops, activity agenda regarding the number of planned and unplanned store visits, expenditures, purpose and motivation of the visit to the shopping district, and socio-demographic information. In order to obtain

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more accurate geo-localized information, state-of-the-art technologies are sometime employed. These technologies can help alleviate the shortcomings of traditional travel surveys (Bricka, Sen, Paleti, & Bhat, 2012; Rasouli & Timmermans, 2014; Shoval & Isaacson, 2006; Stopher & Shen, 2011). The comparative studies between GPS and travel survey data are discussed in Bricka and Bhat (2006), and a summary of modeling shopping destination choice is shown in Huang and Levinson (2015).

However, we identified several shortcomings of these methodologies: first, the application of the proposed methodology tends to be spatially limited to street segments or small shopping area, due to the considerable human efforts (i.e., direct observations). This makes it difficult to conduct comparative studies among districts or areas. Second, because of its labor intensity, the data collection can be performed only for a few hours or a few days, resulting, again, in the difficulty of comparative studies. Third, the proposed methodology largely excludes the factor of the walking conditions, such as the moving crowds in the shopping district (e.g., Borgers & Timmermans, 2014; Borgers et al., 2009).

The purpose of this paper is to compensate for the above-mentioned shortcomings. We propose the application of a Bluetooth detection technique (Eagle & Pentland, 2006; Delafontaine, Versichele, Neutens, & Van de Weghe, 2012; Kostakos, O'Neill, Penn, Roussos, & Papadongonas, 2010; Nicolai, Yoneki, Behrens, & Kenn, 2006; O'Neill, Kostakos, Kindberg, Sciek, Penn, Fraser & Jones, 2006 Yoshimura, Girardin, Carrascal, Ratti, & Blat, 2012; Yoshimura et al., 2014) to monitor pedestrians' sequential movements throughout the shopping area. This technique enables us to generate a large-scale dataset of human mobility at the district scale because unannounced tracking methodologies make it possible to collect data for a longer period (i.e., one month), including weekends and special events.

We strategically placed one of our sensors in the metro station, which is one of the important entry/exit points of the study area. This indicates that the scope of our study is the analysis of the behaviors of pedestrians who come to and leave the district by the metro. This spatial selection corresponds with the previous research that intercepted shoppers randomly at the entry/exit point of the shopping district (e.g., Borgers & Timmermans, 2014). That is, our research method enables us to capture data regarding pedestrians' behaviors in the large-scale dataset in quantity, but without biasing their inner thoughts; compared to previous research which captured small-scale data with the attributions or inner thoughts. In addition, our dataset covers a longer period of time, which makes it possible to compare behaviors and how it changes depending on the time of day, and the day of the week. Thus, we try to examine "real and large-scale empirical data" to uncover the pedestrians' behavioral differences between sales periods and normal shopping days, in terms of the special trajectory, visited places, and length of stay in the determined district.

In the following section, we present our methodology and discuss how a Bluetooth detection technique can be a viable alternative to the existing approach, considering the large-scale datasets to be analyzed. In the third section, we describe the design of the experiment in the historical center of Barcelona and the features of the obtained datasets. In the fourth section, we analyze the pedestrians' behavioral differences between the sales period and normal shopping days. The paper concludes with a summary of findings and discussions.

2. Methodology for the analysis framework

The Bluetooth detection technique is based on the systematic observation method in the framework of the "unobtrusive measures" (Webb, Campbell, Schwartz, & Sechrest, 1966). This makes use of people's unconsciously left *digital footprints* or "data exhaust" (Mayer-Schönberger & Cukier, 2013; p. 113). The Bluetooth detection technique can be classified as a passive data collection technique, which is in contrast to the active data collection (see a review of data collection classification in Yoshimura et al., 2012, 2014). The following are the advantages of Bluetooth detection technique compared with other existing methods for the analysis of shopping behaviors.

First, this technique enables us to collect a large-scale set of pedestrian behaviors. Although interviews, questionnaires, direct observations (Flick, 2009), and active mobile phone tracking with or without GPS (Shoval, McKercher, Birenboim, & Ng, 2015) can provide us with more accurate and detailed information about the actual trip made by a person, each of them tends to result in relatively small-scale sample sizes because they require asking participants to bring devices in advance. Second, passive data collection technique does not require the labor intensive (i.e., direct observation for several hours). This aspect enables us to collect the relevant dataset for a longer period, including during the weekend or a special event. Third, since Bluetooth detection is based on an unannounced tracking system, subjects are not aware of being tracked, resulting in unbiased behavioral data, as expected. Finally, the detection range of Bluetooth is much finer grained than the network-based passive mobile detection technique, which can also generate a large-scale dataset of human mobility (González, Hidalgo, & Barabási, 2008). The detection range of the former is based on the antenna's coverage, which cannot identify pedestrians' locations between streets.

The unannounced tracking system aspect of the Bluetooth technique provides us the above-mentioned advantages over active data collection techniques. However, this aspect also may raise discussions about ethical and privacy issues. MAC address, which can be detected by Bluetooth, is not associated with any personal information (see Versichele et al., 2012, p. 209), so the detection of such information from individual mobile devices still avoids any potential privacy issues. Considering future use and its adaptation for the urban setting condition, including possible changes to the legislative framework in the future, we propose applying a hash algorithm (Stallings, 2011, pp. 342–361) to our sensor in order to maintain the anonymity of the visitors' data by converting the MAC address into a unique pseudonym (Yoshimura et al., 2014). This point makes our research method different from other prior work, which is also based on all of the above-mentioned Bluetooth detection techniques.

3. Study setting

The 1st of February marks the start of the second major discount period in Barcelona, Spain and lasts until the end of the month. Thus, we selected a data collection period from 01/29/2009 to 02/20/2009, resulting in data from more than 4 million unique devices. The choice of this specific season for the research enabled us to analyze the impact of discount days on the pedestrians' behaviors compared with the other normal days.

3.1. Study environment and study settings

The supply of shops on each street is considered one of most important factors affecting pedestrian behaviors in a shopping environment (Borgers & Timmermans, 2005). The density of the population per retail shop in the study area is 0.072, which is the highest one among the district in Barcelona and the second highest one in terms of the dimension (i.e., density per retail shop). Our previous research uncovered that the number of transactions in this district is superior to the number of economic activities