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Exploring spatial relationships among soundscape variables in urban areas: A spatial statistical modelling approach

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HIGHLIGHTS

- Soundscape maps provide useful information for planning the urban sound environment.
- The effects of spatial dependency on soundscape quality were examined using global and local spatial regression models.
- Spatial non-stationarity was found in the relationships between soundscape quality and the primary functions of spaces.

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ABSTRACT

Noise maps based on sound pressure levels are limited in accurately representing how people perceive the sound environment. As a complementary approach to noise maps, soundscape maps can be useful tools for urban planning and design because they provide more information than conventional noise maps to reflect perceived acoustic environments. This study provides an overview of soundscape maps and explores the influence of spatial contexts on soundscapes in urban spaces. Physical, acoustic, and perceptual data were collected on sound environments in various urban areas in Seoul to create soundscape maps. Sound source types (traffic noise, human sounds, water sounds, and birdsongs), psychoacoustic parameters (*loudness* and *sharpness*), and perceived soundscape quality maps were generated and it was found that soundscape characteristics were varied in accordance with the primary functions of a space. Based on the collected soundscape data, global and local spatial regression analyses were conducted to examine the spatial autocorrelation on prediction on soundscape quality, and spatial dependency of soundscape quality was found in both models. In particular, a local spatial regression model based on geographically non-stationary relationships in variables was found to be more effective in understanding soundscape quality in multi-functional urban spaces. These findings could provide useful knowledge for soundscape planning strategies.

1. Introduction

Environmental noise pollution has been gradually growing due to rapid industrialization and urbanization. Many reports have stated that noise adversely affects physiological and mental health (Berglund, Lindvall, & Schwela, 1999; Marquis-Favre, Premat, & Aubree, 2005), and sound environment is considered a critical factor for creating a healthy city (Corburn, 2009; Seidman & Standring, 2010). In this context, Directive 2002/49/EC, known as the Environmental Noise Directive (END), aims to assess and manage environmental noise for creating quiet environments and reducing noise levels that negatively influence human health (EC, 2002).

The noise map is a useful tool to identify noise exposure in a given region and diagnose the area where action is required by providing visual presentation of calculated sound pressure levels (SPLs) from noise sources (Murphy & King, 2010; Seong et al., 2011). Noise maps typically visualize calculated SPLs from environmental noise sources based on a physical model of the environmental noise and the outdoor propagation of sound, and can assess the effects of transportation and other issues during the planning stage (Klæboe, Engelien, & Steinnes, 2006; Lee, Chang, & Park, 2008). Recently, noise monitoring techniques based on mobile noise measurement devices have been investigated to build noise maps, which can be a

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more cost-efficient noise monitoring method than the conventional noise monitoring network system (Can, Dekoninck, & Botteldooren, 2014; Murphy & King, 2016).

Despite these benefits of noise maps, noise maps are insufficient to achieve a better urban sound environment. The urban sound environment consists of various sound source types including biological, geophysical, and anthropogenic sounds, which positively or negatively influence the perceived sound quality (Axelsson, Nilsson, & Berglund, 2010; Brown, Kang, & Gjestland, 2011; Guastavino, 2006; Hong & Jeon, 2015; Jeon, Lee, Hong, & Cabrera, 2011; Jeon, Hong, & Lee, 2013; Pijanowski, Farina, Gage, Dumyahn, & Krause, 2011). However, noise maps primarily focus on noise sources such as road traffic, railway traffic, aircraft, and industries (De Kluijver & Stoter, 2003; Ko, Chang, & Lee, 2011; Manvell & Hartog Van Banda, 2011; Vogiatzis, 2012; Wang & Kang, 2011), and do not provide information for pleasant or preferred sounds such as water sounds, birdsongs, and tree rustling (EEA, 2014). In addition, noise maps present SPLs, which are related to a limited degree to the human perception of the sound environment due to the complex interaction between sound and human auditory perception (Kang, 2006; Raimbault & Dubois, 2005; Schafer, 1977).

In order to overcome the shortcomings of noise maps, attempts have been made to produce alternative maps based on the soundscape concept. The notion of a soundscape is defined in ISO 12913-1 (2013) as the "acoustic environment as perceived or experienced and/or understood by a person or people, in context". Many researchers have suggested soundscape maps based on the human perception of the sound environment (Aletta & Kang, 2015; Ge, Lu, Morotomi, & Hokao, 2009; Genuit, Schulte-fortkamp, & Fiebig, 2008; Hao, Kang, & Krijnders, 2015; Kang, 2000, 2002; Liu, Kang, & Behm, 2014; Liu, Kang, Luo, Behm, & Coppack, 2013; Yu & Kang, 2009, 2015). Soundscape map studies can be summarized into three main themes: the sound source map, psychoacoustic map, and perceptual quality map of the sound environment (Aletta & Kang, 2015; Ge et al., 2009; Genuit & Fiebig, 2006; Genuit et al., 2008; Hao et al., 2015; Liu et al., 2014, 2013). Sound source maps provide information on various source types including both noise and positive sources. Liu et al. (2013, 2014) developed sound source maps based on the spatiotemporal variability of perceived sound sources classified into anthrophony, biophony and geophony in urban spaces, and demonstrated that landscape characteristics are related to soundscape compositions. Based on mathematical models of sound emission and propagation, Kang (2000, 2002) conducted sound field mapping based on simulation techniques considering diffusive and reflecting sound fields in both an urban street and square, which may affect the soundscape perception of sound sources. In addition, sound maps for birdsongs (Aletta & Kang, 2015; Hao et al., 2015) and water sounds (Aletta & Kang, 2015; Calarco & Galbrun, 2015) were created in the previous studies. Psychoacoustic maps can provide more information on sound quality perceptions than noise maps (Genuit & Fiebig, 2006). Genuit et al. (2008) drew maps for psychoacoustic parameters including *loudness*, *sharpness*, and *roughness* values in public spaces in Berlin using measured acoustic data. Soundscape quality mapping describing people's subjective perception is a useful tool for soundscape planning. Yu and Kang (2009, 2015) developed soundscape quality maps using an artificial neural network algorithm based on subjective responses to a soundscape in an urban public space. Ge et al. (2009) conducted field measurement and surveys to obtain physical acoustic data and subjective data on soundscapes. Based on the quantitative and qualitative data, they suggest preference soundscape maps in urban areas and explore the relationships between acoustic parameters and landscape factors.

The main focus of previous studies on soundscape mapping has been to visualize the objective and subjective soundscape data using geographical information system (GIS) tools, and then to analyze the relationships among the soundscape data without considering the spatial dependence. Here, spatial dependence means "the propensity for nearby locations to influence each other and to possess similar attributes (Anselin, 1988)." It has been reported that environmental variables such as surface temperature (Chun & Guldmann, 2014; Su, Foody, & Cheng, 2012), noise (Ryu, Park, Seo, & Chun, 2014), and land cover (Kim & Shin, 2016; Su et al., 2012) have a spatial autocorrelation over urban spaces.

Spatial dependence may occur because of the spatial dimensions of the social-cultural and economic aspects in urban spaces (Lesage, 1999), which might be a critical aspect of soundscape modelling. Hong and Jeon (2015) showed that the primary functions, activities, and visual properties of spaces in urban spatial contexts play a significant role in soundscape perceptions in urban settings. These findings imply that a spatial dependence might affect urban soundscapes. However, only a few studies on soundscape maps have considered the spatial dependence when exploring the relationships among the soundscape variables in urban spaces.

In this context, the main objectives of the present study are to create soundscape maps including sound source types, psychoacoustic parameters, and soundscape quality maps, and to examine the spatial dependencies on soundscapes in urban spaces. To achieve these goals, both acoustic measurement and subjective assessments of sound environments were performed in real urban environments. Based on the obtained soundscape data, perceived soundscape quality models were suggested using spatial regression methods.

2. Methodology

2.1. Study area

A northern part of Seoul, Korea (Joong-Gu and Jongro-Gu area), was selected as a case study for creating soundscape maps because the area included various urban contexts such as residential areas, commercial areas, office districts, urban parks, and city streams, which are important for examining the spatial dependency of soundscapes in urban spaces. As shown Fig. 1(a), the study area is approximately 2.0 km^2 with a length of 1.77 km and width of 1.75 km. The case study area was divided using a grid comprised of 125 meshes. The main mesh size (150 m × 150 m) was empirically determined considering both the homogeneous characteristics of visual and sound environments and the efficiency of soundscape measurements within a time period (13:00-17:00) in the case study area. Since the city stream, Cheonggyecheon (35 m × 900 m), and the urban public space, Gwanghwamun Plaza (43 m × 600 m), are long and narrow areas, the mesh size in these areas was 150 m × 50 m (10 meshes) as depicted in Fig. 1(b). Several preliminary field tests were conducted to decide the evaluation positions in the study area. An evaluation point for each grid was determined based on the location considered to best reflect the overall soundscape quality, as shown in Fig. 1(b).

The study area spans a varied urban morphology and consists of spaces with various functions. Similar to a previous study (Hong & Jeon, 2015), the functional types of urban spaces in this study were classified into six categories: 1) residential areas, 2) commercial areas with a high density, 3) commercial areas with a low density, 4) a central business district (CBD), 5) green areas and urban public spaces, and 6) city streams, as indicated in Fig. 1(c).

2.2. Collecting soundscape data

Soundscape data were collected from both perceptual assessments and acoustic measurements of the sound environment in the study area. Regarding perceived acoustic environment, identified