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On the relationship between land use and sound sources in the urban environment

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ABSTRACT

The purpose of this case study was to explore the relationship between land use and sound sources and how to characterize urban environments in this respect. To this end, binaural recordings and 360° videos were used in a listening experiment, where 20 university students assessed the dominance of sound sources coupled with the appropriateness of land use variables and variables of social and recreational activities. Principal Components Analysis showed that the activity-based environment can be explained by two main components related to the degree of man-made features and the density of people. These components are closely associated with sounds.

Introduction

The primary aim of this study was to explore potential relationships between soundscape and urban form, to learn whether this line of research would be worthwhile. The research was focused on possible relationships among activities, land use attributes and perceived sound sources in the urban environment. In addition, the study explored how to characterize urban environments and what attributes are the best descriptors of urban characteristics, taking soundscape into account. The following steps were taken: (1) identifying the appropriateness of human activities in different urban environments; (2) identifying variables of urban morphology used as predictors of PCA components; (3) identifying sound sources profiles; (4) and human activity profiles; (5) determine the relationship between the two and finally (6) identifying which human activities best differentiated among groups of urban activity profiles.

Among western countries, the importance of sound in urban planning may be traced back to the introduction of land use zoning and noise-compatible development in USA at the beginning of the 20th century. According to Radicchi (2019), Kevin Lynch in the 1960 s and Douglas Porteous in the 1990 s criticized planning theorists and highlighted the significance of a multisensory approach, in an attempt to understand physical and social landscapes. This realm of 'sensuous urbanism' linked functionality and activities in modern cities with human experience. In accord with this approach, soundscape planning

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focuses on the human experience of sound, in context (cf. Southworth 1969; Brown 2014; ISO 2014).

People tend to favour natural over manmade environments (e.g., Kaplan 1983; Herzog 1989), contributing to the former being perceived as pleasant. James Russell and co-workers identified an additional dimension, related to the amount of human activity, and developed a two-dimensional model of perceived affective quality of places (e.g., Russell and Pratt 1980; Russell, Ward, and Pratt 1981; Ward and Russell 1981). Axelsson, Nilsson, and Berglund (2010) developed a similar two-dimensional model for soundscape, identifying pleasantness as the first dimension and eventfulness as the second. Pleasantness was positively associated with natural sounds, and negatively associated with technological sounds. Eventfulness was mainly associated with the presence of people.

Several authors, such as Raimbault and Dubois (2005), Nielbo, Steele, and Guastavino (2013), Bild et al. (2018), Estévez-Mauriz, Forssén, and Dohmen (2018), and Romanowska (2018), have highlighted the significance of the urban context – including the function of a place and the corresponding activities – to soundscape. Activities influence the urban form and mobility patterns (Burton, Jenks, and Williams 2000), and consequently the distribution of sound sources within the city, which would affect the soundscape.

Currently, urban planners (in Europe) approach soundscape primarily reactively in terms of noise as part of environmental impact assessment with the main objective of reducing human exposure to high sound pressure levels (SPL) from existing sources. Present legislation shows that society mainly regards sound as an environmental hazard from which the public must be protected (EC 2002).

The soundscape approach considers sound as an environmental resource to be utilized proactively at the planning and design stage. In order to implement this approach in urban planning policy, it is necessary to redefine problems and objectives from mainly reactively abating the pollutant, to proactively promoting the quality of the acoustic environment. This is a change in perspective that we historically have witnessed with regards to the quality of air and drinking water in Europe (EC 1998, 2008). A similar change in the view on soundscape is expected to reduce the need for retroactive noise abatement in the future (cf. Brown and Muhar 2004; Weber 2013; Brown 2014). This approach requires new theoretical models and new tools in urban planning. The present study represents a preliminary step in this direction, exploring whether it is possible to identify any relationship between soundscape and urban form.

Methods

A listening experiment was conducted at the University of Ghent (Belgium), using audio-visual material collected in Sheffield (UK). This guarantees that the participants did not have any preconceptions with regards to the locations included in the experiment.

Case study area

The city of Sheffield was selected as a characteristic example of a medium-sized UK agglomeration. The case study area, depicted in Figure 1, was chiefly located within the circular highway that surrounds the city centre, and delimited by road A61, Netherthorpe Road, Upper Hanover Street, Hanover Way, and St. Mary's Gate. This area includes a variety

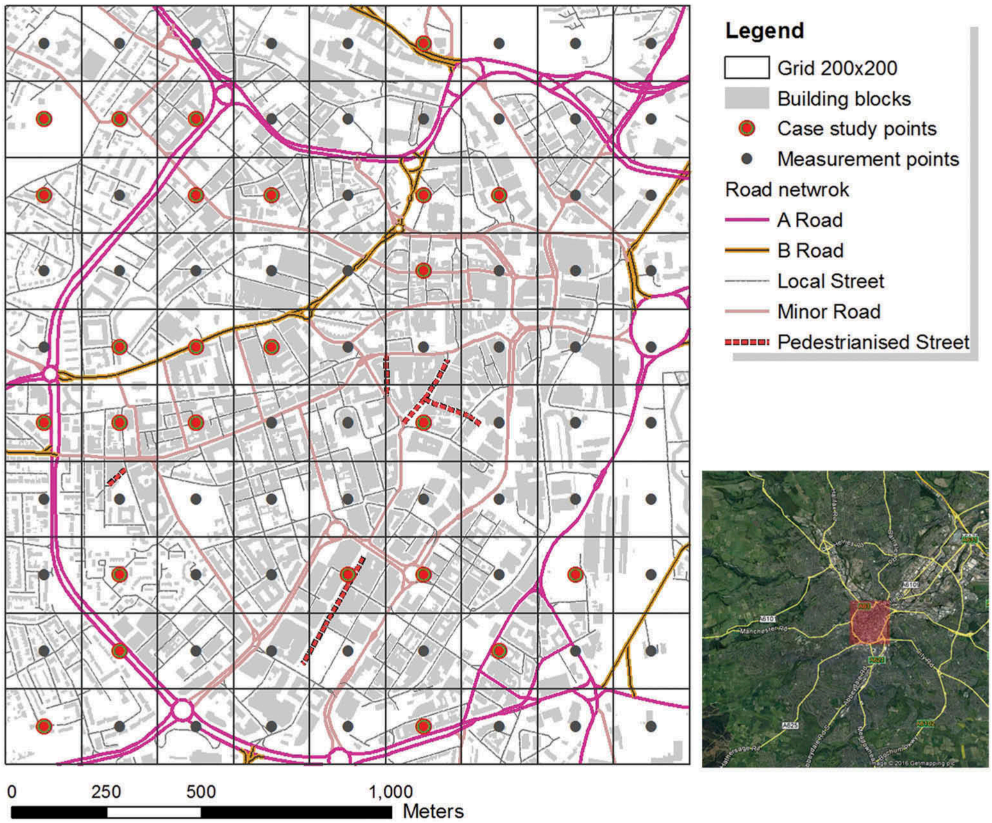

Figure 1. A map of the case study area, including measurement and case study points.

of land use types, such as the old commercial city centre, small industries, residential areas, and green areas. Moreover, there is a plurality of infrastructure types, including the railway station, tram and bus lines, as well as the four typical UK categories of road network (A roads, B roads, minor and local roads) as classified by the Ordnance Survey (2014, 67). The case study area measured 3.8 km^2. To aid the analysis, a 200 × 200 m grid was applied, dividing the area into 90 tiles. The centroid of each tile was decided to be the primary measurement point for sound pressure levels and binaural recordings, provided that accessibility was granted. In opposite cases, the closest outdoor publicly accessible point served as an alternative solution. Morphological variables, presented in Table 1B below, were also considered for each point in order to test their effect on the overall acoustic environment. For example, the 'Road Width/Building Height' ratio was expected to be lower in areas close to the city centre, where commercial activities take place.

Participants

The participants were 20 undergraduate and postgraduate students from Ghent University, aged 23–33 years (16 males, 4 females; M_{age} = 27.5 yrs. SD_{age} = 2.8). They were recruited as volunteers through an open invitation. The variety of their origin covers

Table 1. Social and recreational activities, land uses and morphological variables under investigation.

A. Social and recreational activities, and land uses	
Social and recreational activities	**Land uses**
Appreciating cultural heritage	Car parking
Appreciating inland water	Industrial activity
Boating – Fishing	Offices
Escaping city stress	Residence
Active street life	Road – Rail transportation
Experiencing peace – quiet	Student work (School – University)
Individual outdoor activities	
Nature appreciation	
Outdoor informal games	
Picnic – Barbecue	
Restaurants – Cafes	
Shopping	**Sound sources**
Conversing – Chatting	Traffic
Time with friends – family	People
Swimming – Bathing	Natural sounds
Walking – Jogging	Construction sounds

B. Morphological variables
Ratio of road width to the average building height around the measurement point (Road Width/Building Height)
Road coverage (m^2) within the 200 × 200 m tile
Distance (m) to the closest major road
Distance (m) to the closest minor road
Green space coverage (m^2) within the 200 × 200 m tile

mostly Europe (19), apart from one participant from China. All of them were living in Ghent at that period, and six had Dutch as their mother tongue. Sixteen participants had visited England at least once. None of them had visited Sheffield.

Experimental stimuli

The experimental stimuli were created from auditory and visual material recorded in 25 out of the 90 locations presented in Figure 1. The selection criterion was to choose sites from all sorts of land use categories (commercial, residential, industrial, and others), as described in the Unitary Development Plan of Sheffield (Sheffield City Council 1998). The 25 locations included three locations in urban recreational areas, nine in urban residential areas, five in urban commercial areas, two in pedestrian streets, one in an education services area, two by major roads, two in light industrial units and one in a parking area. In addition, a broad range of soundscapes was sought, with a great diversity of sound sources, including the sound of technology, people and nature (cf. Axelsson, Nilsson, and Berglund 2010).

With regards to the audio part of the stimuli, a researcher recorded the equivalent continuous sound pressure levels ($L_{Aeq,3\ \mathrm{min}}$) and conducted binaural audio recordings in the morning hours (09:00–12:00), as a peak time period, during four working weeks. The equivalent continuous sound pressure levels varied between 51.1 and 89.9 dB(A). From each binaural audio recording, the first author selected a 30 s excerpt to represent the local acoustic environment. Short duration samples can be justified in light of previous research or documentation (e.g., Axelsson, Nilsson, and Berglund 2010;

Oldoni et al. 2015; ISO 2018). The excerpts can be considered representative of the assessment sites as the purpose of the study was to explore whether it is possible to identify any relationship between soundscape and urban form and not to provide a soundscape map of Sheffield. To convey the nature of the 25 locations to the participants, videos were created using Google Street View, making a 360° panoramic camera sweep at each point. The speed of the camera sweep was adjusted so that the duration of each video was 30 s. The audio (wav) and video (mpeg4) were merged together using the Camtasia Studio software.

Equipment

For the on-site audio recordings, the equipment included a stereo microphone kit (DPA 4060) connected to a digital audio recorder (R-44 Edirol), a mini microphone (Micw i436), and a sound calibrator (CAL21). The '*Audiotool*' Android application, installed on a mobile phone with the Micw i436 attached, was used to record the sound pressure levels at each location. The selection of the equipment described above aimed at showing that reasonably representative physical measurements can nowadays be obtained with affordable hardware and software. However, the designer should not have to conduct empirical investigations of this sort. Rather the long-term objective of this line of research is to develop a more general model for soundscape planning and design that would guide design decisions.

The experiment was conducted in a soundproof listening room. The binaural soundscape excerpts were reproduced in headphones (Sennheiser HD 280 Pro) fed by a laptop computer (Dell Inspiron 7720) with an IDT sound card (24 bits, 48 kHz) and at the authentic sound pressure levels. This method of audio reproduction provides for a high degree of realism, preserving the spatial information in the audio signal. The video image was presented in full screen mode on the laptop screen (17″) at a distance of approximately 60 cm in front of the participant. The original audio signals were calibrated using a dummy head (B&K 4128-C) and 0.1″ microphones (Knowles FG-23329-P07).

Data collection tool

Data was collected through a questionnaire built in the SurveyGizmo platform and accessed through an Internet browser. For each of the 25 stimuli, the participants responded to two questions corresponding to 26 variables.

First, the participants assessed how dominant they perceived four different sound sources to be: a) natural sounds, b) traffic sounds, c) sounds from people, and d) construction sounds. For each sound source they responded by the aid of a 100-point slider bar, corresponding to a digital version of a visual analogue scale. The four scales were delimited by the end labels 'Do not hear at all' and 'Completely dominant.'

Second, to provide a characterization of the location, the participants assessed the extent to which 16 social and recreational activities as well as the 6 land uses, presented in Table 1A, were appropriate for the location. For example, imagine that that location was at a roadside and the question was to what extent the location was appropriate for a picnic. For each of these 22 response items, the participants responded by the aid of a 100-point slider bar, delimited by the end labels 'Not appropriate' and 'Perfect match.' The 16 social and recreational activities were a refined set based on the set that Lavia, Axelsson, and Dixon (2012) used (see also Axelsson 2015). The six land uses were added for the purpose of the present study.

The two questions were always presented in the same order for all 25 stimuli and to all participants. However, to avoid order effects in the responses, the order of the response items was randomized for every question and participant (i.e., for the four sounds sources in the first question, as well as the 16 social and recreational activities and the six land uses in the second question).

Experimental procedure

The two questions were presented in the same sequence for every participant. On average, the experiment duration was one hour. Participants were allowed to watch each of the 25 stimuli as many times as needed. The experiment was completed in eleven days with daily sessions between 10:30 am and 07:30 pm.

Results

The first two sections present the results for the relationship between soundscape and the urban form. Following on the next two sections present the results of a stepwise procedure for investigating the characteristics of urban environments, leading to the section presenting the conclusions of this investigation.

Components of land use and sound sources

Arithmetic mean values were calculated across the 20 participants for each of the 25 stimuli, and for all the 26 response items in the questionnaire (sound sources, activities and land uses included). This resulted in a 25 × 26 data matrix, where the rows represented the 25 experimental stimuli and the columns represented the 26 response items. Pearson's product moment correlation coefficients were calculated for all pairs of the 26 response items, and the correlation matrix was subjected to a Principal Components Analysis (PCA; SPSS 22 for Windows). The components extraction method was based on a fixed factor solution of two components. The number of components was calculated based on the scree plot, which shows the percentage of variance explained, as a function of the number of components. Components 1 and 2 explained 49% and 23% of the variance in the set of data, respectively. Thus, the 26 response items were reduced into two orthogonal, latent variables – called principal components for a PCA – that may represent the set of data to a high degree (72% explained variance in total).

Variables associated with infrastructure (road – rail transportation, car parking) and work-related activities (industry, offices) had negative loadings on Component 1 (C1), while social and nature-related activities had positive loadings. There was also a negative association between traffic and construction sounds with Component 1 and a positive association with natural sounds. Consequently, Component 1 seemed to represent natural versus manmade environments. For Component 2 (C2) there was a positive association with shopping, active street life, restaurants – cafes and socializing. Similarly – concerning the sound sources –

there was a positive association only with people's sounds. Consequently, C2 is related to the proximity to the commercial city centre and the density of people. To use Components 1 and 2 in the stead of the 26 response items in further analyses, component scores were calculated (SPSS 22 for Windows).

Relationship between activities, land use and urban morphology

In order to investigate the relationships between activities, land use and urban morphology, data were cleaned from two outlier points, and two backward, linear regression analyses were conducted. Component scores of Components 1 and 2 from the PCA were regressed on the five urban morphology variables presented in Table 1B. Table 2 presents the Pearson's coefficients of correlations.

Component 1 (C1) was best predicted by green space coverage ($\beta = 0.65$, $t = 4.0$, $p = 0.001$), as well as the distance to minor roads ($\beta = 0.41$, $t = 3.0$, $p = 0.006$), ($F = 14$, $p < 0.001$, $R^2 = 0.66$). There was also a positive association with green space coverage ($r = 0.74$, $p < 0.001$) and the distance to minor roads ($r = 0.49$, p = 0.016). Thus, the larger the green space coverage and the larger the distance from minor roads, the more likely it was for a place to be perceived appropriate for leisure activities, allowing for natural sounds to dominate.

Component 2 (C2) was best predicted both with road coverage ($\beta = 0.49$, $t = 3.1$, $p = 0.006$) and the distance to major roads ($\beta = 0.54$, $t = 3.4$, $p = 0.003$), ($F = 10.1$, $p = 0.01$, $R^2 = 0.50$). In this case, green space coverage was negatively associated with Component 2 ($r = -0.47$, p = 0.025). However, in the regression model it was excluded as a predictor, because the other two variables could provide a higher R^2 value. Thus, it is deduced that Sheffield city centre is deprived of green spaces; it presents areas with high road coverage and includes points away from major roads and particularly the Ring Road.

Typology of sound sources

To investigate the characteristics of the 25 locations with regards to soundscape, the data was subjected to a cluster analysis. The aim was to group the 25 sample points (rows) – based on the presence and the variability of each one of the 4 sound sources (columns) – and identify possible profiles. The 25 × 4 matrix was initially used for a hierarchical clustering, using the Ward's method with Squared Euclidian distances (SPSS 22 for Windows). The data was arithmetic mean values calculated across the 20 participants. The agglomeration schedule and the dendrogram suggested that three clusters can represent the data structure effectively.

Table 2. Pearson's correlation coefficients between C1, C2 and the five morphological variables (Table 1B).

	C1	C2	3	4	5	6
C2	−0.04					
3. Road Width/Building Height	−0.16	−0.26				
4. Road coverage	−0.33	0.46*	0.46*			
5. Distance to major road	0.10	0.51*	−0.47*	−0.06		
6. Distance to minor road	0.49*	−0.26	0.22	−0.01	−0.21	
7. Green space coverage	0.74**	−0.47*	0.31	−0.51*	−0.24	0.46*

* p < 0.05
** p < 0.001

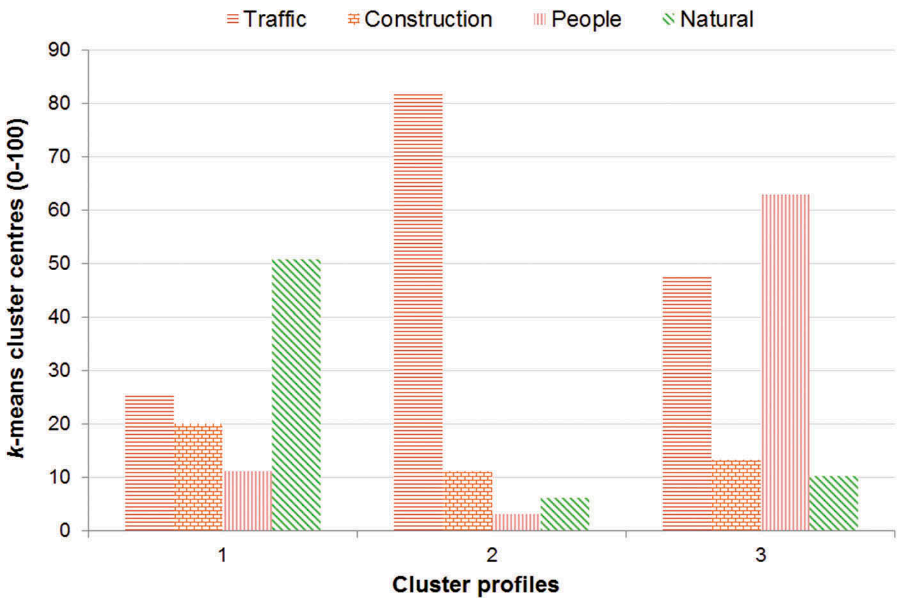

Figure 2. *k*-means cluster centres for sound sources profiles.

In a second step, a *k*-means clustering algorithm was applied to identify the cluster membership and cluster centres for each one of the 25 case study points using a fixed solution of three clusters. The outcome of this method for the current dataset is presented in Figure 2 showing the cluster centres for each sound source in the three profiles. According to the cluster membership, 'Profile 1' presenting low cluster centres for traffic (25.3) and construction sounds (20.2), while natural sounds were the most prevalent (50.9). In this profile human presence was limited with the lowest value (11.3) compared to all other sound sources. From a planning perspective, the cluster analysis shows the types of urban environments and how to characterize them with the aid of the 14 attributes that discriminate among the three clusters.

In cluster 'Profile 2', traffic noise had the highest cluster centre (81.9) with the rest of them to present minimum variations and range in a very low level. Similar to the first cluster, human sounds presented the minimum cluster centre (3.2) with natural sounds and construction sounds to follow.

Contrary to the previous two cases, cluster 'Profile 3' was dominated by human sounds (63.1) with the presence of traffic (47.6) to be also significantly evident, but to a lower extent. In this case construction and natural sounds presented slightly higher values in the cluster centres compared to cluster '2', but lower compared to cluster '1'. In total, four places belonged to the first profile, eleven to the second and ten to the third. These results are further explored and interpreted in the discussion section.

Typology of places

To explore the characteristics of the 25 locations with regards to social and recreational activities and land uses, a 25 × 22 data matrix was created. The rows represented the 25 experimental stimuli and the columns represented the 22 social and recreational activities and land uses as shown in Table 1A. The data was arithmetic mean values calculated across the 20 participants.

First, the data matrix was subjected to a hierarchical cluster analysis, using the Ward's method with Squared Euclidian distances (SPSS 22 for Windows). Through inspection of the agglomeration schedule and the dendrogram, three clusters were identified.

Second, the data matrix was subjected to a *k*-means cluster analysis. As presented in Table 3 (*column: land use*), four of the experimental stimuli were located in Cluster 1, 18 in Cluster 2, and 3 in Cluster 3. Figure 3 presents the components score plot based on the PCA. The data points represent the 25 experimental stimuli, marked according to the three clusters they belonged to. These results are further explored and interpreted in the following section.

Relationship between sound sources and land use activities

The association between sound sources and land use activity profiles was tested using a Chi-Square test of independence. The two variables tested refer to: a) the cluster membership of sound sources and b) land use activities. This resulted in a matrix of 25 × 2. Rows represented the 25 locations and columns the 2 cluster solutions from the two previous sections.

There was a statistically significant association between the two cluster solutions ($\chi^2_{4,25} = 11.39$, $p = 0.023$). As shown by the contingency table in Table 4, areas in Cluster 1 were mainly residential and consequently more likely to present natural (+1.4)

Table 3. Distribution of case study points by cluster sorted according to land use variables cluster membership. In the land use column, the following matches are: '1' Residential, '2' Economic and industrial, '3' Commercial.

			Cluster	
Point ID	Type	$L_{AEq,3\ min}$	Sound sources	Land use
1	Recreational area	51.1	1	1
20	Residential area	60.9	3	1
64	Recreational area	69.6	1	1
73	Recreational area	72.5	3	1
6	Residential area	77.1	2	2
11	Residential area	71.5	2	2
16	Residential area	62.6	3	2
24	Commercial area	76.3	2	2
37	Education services area	59.6	2	2
38	Residential area	62.7	3	2
39	Education services area	54.3	2	2
47	Residential area	58.5	3	2
48	Commercial area	73.6	2	2
49	Commercial area	56.2	2	2
60	Recreational area	66.9	3	2
66	Parking area	71.3	2	2
67	Light industrial unit	74.1	1	2
69	Parking area	67.4	2	2
74	Residential area	77.9	2	2
75	Residential area	89.9	1	2
87	Residential area	80.1	2	2
70	Residential area	73.1	3	2
23	Commercial area	76.9	3	3
26	Recreational area	57.6	3	3
42	Commercial area	61	3	3

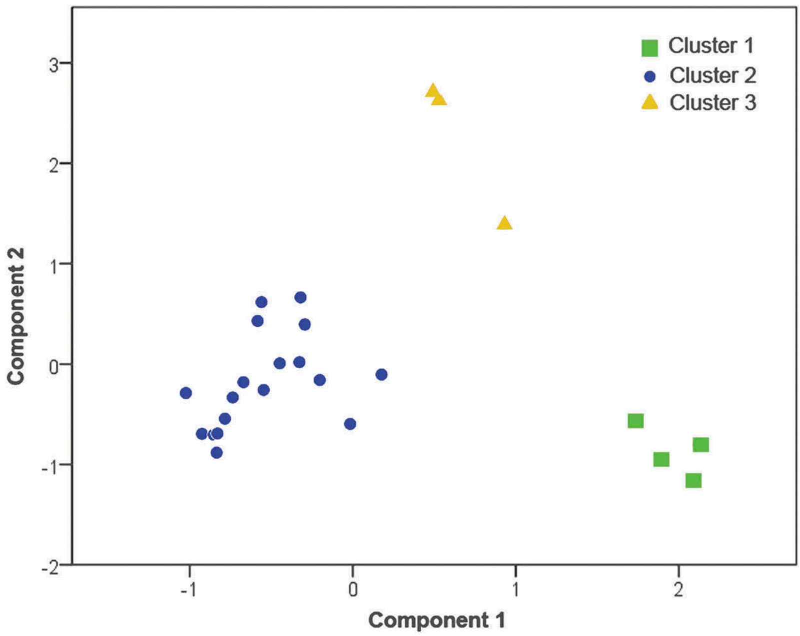

Figure 3. Principal components scores for 25 experimental stimuli.

Table 4. Contingency table of sound sources and land use activity profiles. In parenthesis, the difference between observed and expected values.

			Land use activity profiles			
			Cluster 1	Cluster 2	Cluster 3	Total
Sound source profiles	Natural sounds	Observed	2 (1.4)	2 (−0.9)	0 (−0.5)	4
		Expected	0.6	2.9	0.5	4
	Traffic sounds	Observed	0 (−1.8)	11 (3.1)	0 (−1.3)	11
		Expected	1.8	7.9	1.3	11
	Human sounds	Observed	2 (0.4)	5 (−2.2)	3 (1.8)	10
		Expected	1.6	7.2	1.2	10
Total		Observed	4	18	3	25
		Expected	4	18	3	25

and human sounds (+0.4) than expected. Areas in Cluster 2 presented a mixed land use character and thus more likely to be associated with traffic sounds (+3.1) and less probable with natural (−0.9) and human sounds (−2.2). In this cluster the observed and expected difference of traffic was the highest among all the three profiles. Finally, areas belonging to Cluster 3 were mainly commercial spots more likely to appear human sounds (+1.8) and less likely to be affected by traffic sounds (−1.3). Natural sounds in these areas were almost imperceptible (−0.5).

Relationship between activities, land use and type of place using multivariate analysis

In order to investigate which of the 22 activity and land use variables (Table 1A) best differentiated between the three clusters, a one-way multivariate analysis of variance

(MANOVA) was conducted. It was selected as an alternative to Multinomial Logistic Regression, which was not possible to be applied due to 'complete separation of data'.

The assumption of normality was tested, using the Shapiro-Wilks test and the histograms of the standardized residuals for each variable. The homogeneity of variances was tested using the Levene's test. Finally, the assumption of multicollinearity was assessed using the VIF factor, by eliminating the violating predictors. For this process, a regression model was applied using the equivalent sound pressure level (Table 3) at each case study point as the dependent variable and the 22 activity and land use variables as predictors. In total, seven variables were discarded, resulting in a 25 × 15 data matrix. Then, the variable of land use cluster membership was added to the data matrix (Table 3). The data matrix was subjected to MANOVA using an 'unbalanced model' due to the different number of sites in each cluster.

The effectiveness of the model was assessed using the Pillai's Trace index. It showed that, overall, there were statistically significant mean value differences among the three clusters for the land use variables ($F_{30,18} = 26.3$, $p < 0.001$, Pillai's Trace = 1.95, $\eta_p^2 = 0.97$). Details for the 14 statistically significant variables – those able to discriminate between the three clusters – are reported in Table 5. It includes the mean values (M) for each cluster, the standard errors of the means (±1 SE), *F*-values, *p*-values, and partial eta squared (η_p^2). The variable 'Student work' was not statistically significant ($F = 2.08$, $p = 0.149$) and omitted. The effect size (η_p^2) was large for all variables and above the cut-off value of 0.14 (Cohen 1988).

According to Table 5, Cluster 1 presented the highest mean values for 'Residence,' (77.3) 'Walking-Jogging-Running' (63.4), 'Spending time with friends-family' (46.6) and 'Nature appreciation' (44.1). This means that on average the 20 participants perceived the former activities and land uses as appropriate in the locations grouped into this cluster. Thus, this cluster was interpreted to represent *residential areas*.

Cluster 2 was representative of 'Road-Rail transportation' (47.6), 'Offices' (43.5), 'Car parking' (39.2) and "Industrial activity (31.8). This cluster scored low in 'Nature appreciation' (2.9) and was representative of *employment or industrial areas*.

Table 5. Mean values (*M*) and standard errors of the means (±1 *SE*) for three land use types, as well as *F*-statistics from the MANOVA test of between-subjects effects with land use variables. The table is sorted in descending order for partial eta squared (η_p^2).

	Land use type [M (SE)]					
Land use activities	Cluster 1	Cluster 2	Cluster 3	F(2,13)	*p*	η_p^2
Time with friends-family	46.6 (2.6)	7.8 (1.1)	44.0 (4.9)	128.5	< 0.001	0.92
Walking-Jogging	63.4 (2.8)	14.8 (1.4)	31.8 (2.7)	124.5	< 0.001	0.92
Nature appreciation	44.1 (7.1)	2.9 (0.8)	3.0 (1.3)	77.6	< 0.001	0.88
Restaurants-Cafes	15.4 (1.9)	13.7 (1.4)	58.4 (9.1)	50.0	< 0.001	0.82
Conversing-Chatting	43.5 (7.7)	13.2 (1.7)	51.6 (5.9)	35.1	< 0.001	0.76
Active street life	16.1 (4.6)	14.4 (2)	59.7 (6.7)	33.1	< 0.001	0.75
Shopping	7.8 (0.9)	15.8 (2.2)	67.1 (13.7)	32.1	< 0.001	0.75
Residence	77.3 (6.4)	30.4 (3.6)	20.2 (6.2)	19.4	< 0.001	0.64
Road-Rail transportation	11.8 (2)	47.6 (3.6)	8.4 (1.7)	18.8	< 0.001	0.63
Appreciating cultural heritage	13.0 (4.1)	6.6 (0.9)	30.9 (8.8)	18.6	< 0.001	0.63
Car parking	17.3 (3)	39.2 (3.9)	6.3 (4.3)	8.4	0.002	0.43
Appreciating inland water	15.2 (3.6)	3.0 (0.5)	13.2 (10.3)	8.2	0.002	0.43
Industrial activity	1.2 (0.5)	31.8 (4.8)	2.3 (1.1)	7.2	0.004	0.40
Offices	13.3 (2)	43.5 (4.1)	33.4 (0.7)	6.6	0.006	0.37

Only statistically significant variables included.

Cluster 3 was typical of commercial and social activities, since it presented the highest mean values in 'Shopping' (67.1), 'Experiencing active street life' (59.7), 'Restaurants – Cafes' (58.4) and 'Socializing – Conversing – Chatting' (51.6). It was interpreted to represent Sheffield city centre, or *commercial areas*.

In the next step, the Games-Howell post hoc test was used to highlight the statistically significant mean differences ($p < 0.05$) among the three clusters as shown in Figure 4. This test was applied because the sample size was relatively small and equal variances could not be assumed. The relevant differences also represent the land use incompatibilities in the different cluster combinations.

Apparently, 'Residence' presents the highest incompatibility in Clusters 1–2 (Residential – Employment) and Clusters 1–3 (Residential – Commercial). The same happened with 'Walking – Jogging – Running' and 'Nature appreciation'. On the other hand, 'Industrial activity', 'Road-rail transportation', 'Car parking' and 'Spending time with friends' were highly incompatible when comparing Clusters 1–2 and 2–3. Finally, it is important to consider that activities related to street life and socializing were contrasting in the 'Employment – Commercial' cluster or in the 'Residential – Commercial' one. The latter signifies the essential link between shopping – socializing and anthropic sounds, which was anticipated to some extent in the 'Residential – Commercial' cluster as well. Nevertheless, its absence is an element of further investigation on the effective connection between soundscape and planning standards. For each of the three clusters, Figure 5 presents three examples of footages from the 25 videos.

Finally, when validating the findings by rerunning a *k*-means cluster analysis with only the 14 statistically significant variables presented in Table 5, almost all experimental stimuli retained their cluster membership (see cluster 'Land use' in Table 4). The only

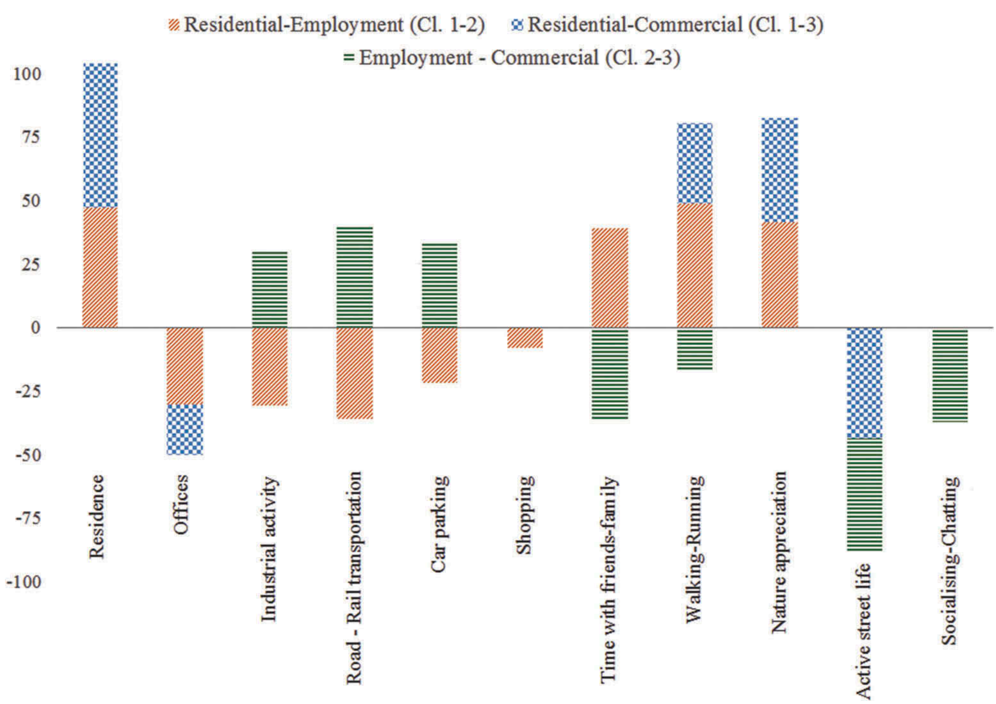

Figure 4. Mean differences (MD) of land use activities based on Games-Howell post-hoc test.

Figure 5. Footages from the videos used on the experiment for the three clusters.

exception was Point 47, which moved from Cluster 2 (Economic and Industrial) to Cluster 1 (Residential).

In summary, in characterizing the 25 locations investigated in Sheffield, three types of locations were identified. They were named *Residential* (Cluster 1), *Employment or Industrial* (Cluster 2) and *Commercial* areas (Cluster 3). In addition, 14 variables (Table 5) were identified that distinguish between these clusters. Taken together, the results show that soundscape is an integral part of the character of urban environments, because soundscape is a function of the urban form, which distributes the sound sources.

Discussion

The current results show that there was a meaningful relationship between the urban form and the distribution of activities and sound sources in the urban environment in Sheffield, affecting the soundscape. This proves that it is worthwhile investigating such relationships further – also in other cities – with the objective to develop a general model that may guide urban planners and designers in creating environments of high acoustic quality. This includes a diversity of soundscapes, such as vibrant local downtown areas, tranquil green spaces, and areas with a relaxing social atmosphere, as opposed to congested traffic arteries. The potential of such avenues is currently being explored in Europe in the process of revising the Environmental Noise Directive (EC 2002) to possibly also include an urban planning and design framework in parallel to noise abatement. The most recent example of good practice comes from the Welsh Government, which addressed the importance of soundscape alongside with air quality in the updated 'Noise and Soundscape Action Plan' (2018–2023).

In some European countries such as Sweden, where soundscape research was established some 20 years ago, more local authorities are investigating what soundscape planning and design may entail in practice. For example, the town of Trelleborg, in the south of Sweden, recently used acoustic design as a criterion in the development of a new detail plan for the regeneration of its old town centre. In England, Brighton has shown a similar interest in the developments of the Valley Gardens project. At the same time, national authorities in Sweden are coordinating their work to promote a new approach towards creating environments of high acoustic quality, as opposed to noise abatement alone. The present results – if not directly applicable – may serve as inspiration in this endeavour and for moving ahead, by shining a light on the prospects of urban acoustic design.

At the urban level, this study goes beyond the findings of Kaplan (1983) who mentioned that among urban settings those containing natural elements are mostly preferred. Specifically, the interpretation of the first Principal Component, C1, suggests that an environment is perceived as 'natural' and appropriate for recreational activities when the land use allocation in these areas provides high proportion of green spaces and larger distance from roads. The consideration of such criteria can possibly address issues of environmental justice in cities (Wolch, Byrne, and Newell 2014).

The connection of C2 with the proximity to the city centre and the presence of people is in line with the study of Yang and Kang (2005) who also recognized the prevalence of human sounds in particular areas of Sheffield city centre. Similarly, Davies et al. (2013) and Aletta and Kang (2018) considered vibrancy from human voices as one of the two principal components of soundscape. Places where human sounds prevail have been considered as ideal urban soundscapes (Guastavino 2003, cited in Raimbault and Dubois 2005). In contrast, anthropogenic sound sources can be experienced as a disturbance in a natural environment (Iglesias Merchan, Diaz-Balteiro, and Soliño. 2014).

Statistically significant differences among the three clusters of locations were found in terms of 14 land use activities. Chiefly, Cluster 2 was associated with 'Road – Rail transportation'. Broadly speaking, this is partly in contrast to Raimbault and Dubois (2006) who found that traffic noise was the obvious outstanding sound source of the urban environment (cf. Southworth 1969).

The present line of research, if explored further, may lead to the development of soundscape maps and a more general model for soundscape planning and design, as a complement to noise maps and noise abatement. The case study of the Sheffield city centre can be regarded as an initial step in this direction, although the three separate clusters, with apparently mono-functional land-use, where identified among the 25 case study locations, might not be generalized.

It is understandable if the interested reader would have expected and hoped for more answers from this study related to how to design urban space, or how to better integrate the city's functions. However, this would be to expect too much from a single case study, which potentially suffers from some methodological limitations. The 25 locations included in this study were selected among the centroids of 90 cells in a grid placed over the Sheffield city centre. This may not necessarily provide the most representative locations and the best sample size. The time for sound recordings were restricted to the morning hours. This makes the recordings comparable across the locations, but not necessarily representative of the individual locations. Using Google Street View videos as visual material may also restrict how people experience the locations. Future studies should seek to use immersive virtual reality technology providing an even more realistic representation of the assessment locations, and to validate the laboratory findings against results obtained in situ. Consequently, more research is needed from more cities, regions and countries to create a more general model of the relationship between soundscape and the urban form. Such a model should guide urban planners and designer in how to design urban areas of high acoustic quality based un the urban form and land use.

Conclusions

The purpose of this case study was to investigate the relationship between land uses and sound sources in the urban environment. The main conclusions are:

- This line of research investigating relationship between land use attributes and perceived sound sources in the urban environment is worthwhile continuing.
- The combination of land use and sound sources can be described in terms of two Principal Components. Component 1 represented natural versus manmade environments, and Component 2 represented the proximity to the commercial city centre.
- Component 1 was best predicted by and positively associated with green space coverage, as well as the distance to minor roads. Component 2 was best predicted and positively associated both with road coverage and the distance to major roads.
- Three sound source cluster profiles were formed. 'Profile 1' presented the highest value for natural sounds and the lowest for human sounds. In 'Profile 2' traffic noise dominated, while in 'Profile 3' human and traffic sounds were prevalent.
- Three clusters were identified for the urban activity profiles. 'Cluster 1' included recreational and residential areas with many green features. 'Cluster 2' presented mainly a mixture of residential and commercial type. Finally, 'Cluster 3' was purely characterized by commercial areas.
- The statistical significance between sound sources and land use activities showed that residential areas in 'Cluster 1' were more likely to present natural and human sounds. Areas in 'Cluster 2' were more likely to be associated with traffic sounds. Areas in 'Cluster 3' were more probable to be linked with human sounds and less with traffic sounds.
- High mean differences among the three land use types were identified. In particular, 'Residence' and activities related to 'Nature' presented the highest differences between Residential and Economic–Industrial areas. Similar results were observed between 'Residential' and 'Commercial' areas with the highest differences to be noted in 'Experiencing active street life' and the residence suitability. Ultimately, the lack of social activities was also distinctive in the comparison between 'Commercial' and 'Economic-Industrial' areas, coupled with the predominance of activities related to road and rail transportation in the latter case.

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