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Research Article

Efstathios Margaritis* and Jian Kang

Soundscape mapping in environmental noise management and urban planning: case studies in two UK cities

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1 Introduction

The current European practice in noise policy the last fifteen years is primarily focused on the application of guidelines and measures related to noise reduction as described in the Environmental Noise Directive (END) [1]. In the same wavelength, noise action plans and all the supportive documentation for strategic noise mapping [2] are focused mainly on improving the accuracy of the END and increase the precision of the reported population exposed at high noise bands.

In this framework, mapping is a useful tool to aid the planning and design process [3]. Some studies have tried to formulate a better traffic model by using dynamic noise mapping techniques [4, 5] or even data extracted from participatory noise mapping techniques [6, 7]. Moreover, the need to combine a holistic approach in environmental noise policy - by combining the noise mapping with the soundscape approach - has recently been raised by the European Environmental Agency (EEA) in the Good Practice Guide on Quiet Areas [8].

However, the ultimate aim is a gradual incorporation of the soundscape design in the planning process in a successful way. This process can be brought into reality starting from a top-down approach initially in the policy stage and then elaborating the process in the macro-scale. At that level, prediction maps refer to a specific landscape and cover areas larger than streets or squares. Through this process, thematic maps can be developed as an additional layer of landscape information [3]. As Kang [9] mentions: "...it is important to put soundscape into the in-

tentional design process comparable to landscape and to introduce the theories of soundscape into the design process of urban public spaces". Lately, suggestions of applied soundscape practises were introduced in the Master plan level thanks to the initiative of the local authorities. [10] presented this approach for the city of Brighton, while more examples of cooperation between Municipalities and Universities around Europe were presented by [11], highlighted in the EU SONORUS project.

Therefore, this paper has a dual aim. Primarily, the development of a mapping model to aid soundscape planning and secondly the implementation and the assessment of its effectiveness in two UK cities with similar land use characteristics and different road network structure.

2 Methods

2.1 Planning framework

In terms of a common framework for soundscape in the planning process, [12] have described the stages in the UK urban planning system, where soundscape can be incorporated in. [13] inspired by the previous model divided the acoustic planning process in two phases, as shown in Figure 1. The first one (Phase 1) refers to the achievement of general noise objectives, such as the maximum noise levels in facades and the second one (Phase 2) refers to the detailed acoustic design process through the combination of appropriate urban activities and sound sources as previously investigated by [14].

In this process, soundscape consideration and in particular soundscape mapping is more suitable in the first phase (Figure 1), where the analysis of the existing situation is required. However, the assessment process can also follow a feedback routine between "Phase 1" and "Phase 2" depending on the number of the planning scenarios. Precisely, the most widely applied tools for soundscape mapping in terms of content includes the spatial variability of sound sources and the variability of perceptual at-

*Corresponding Author: Efstathios Margaritis: Durham University, United Kingdom; Email: efstathios.margaritis@durham.ac.uk
Jian Kang: University of Sheffield School of Architecture



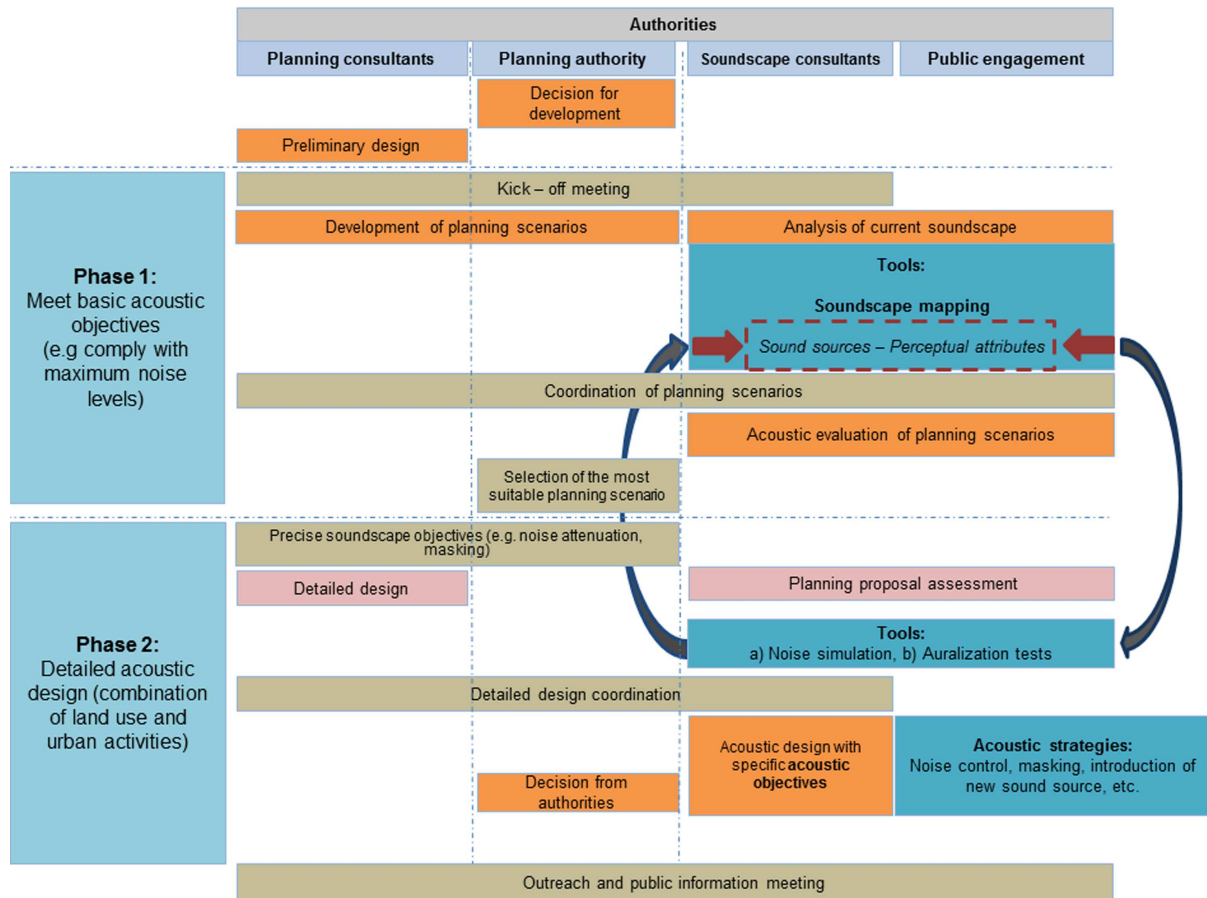


Figure 1: A suggestion for the incorporation of soundscape mapping in the planning framework and the authorities involved based on the model of [13].

tributes (Figure 1). A detailed representation of the individual steps in the soundscape mapping framework is presented in Figure 2. Although there are five main steps, “soundscape profiling” is presented as an additional sixth provisional stage, since it comes naturally in the whole process and can provide specific details relevant to the character of the area.

2.2 Sampling strategy

Depending on the geometry of the case study site, the sampling method and location points should be adjusted accordingly. For practical purposes, sampling points outside the main sampling area should also be considered to allow the interpolation algorithm to produce a broad enough raster surface. Both the sample size and the position (density) of the evaluation points are guides for a successful interpolation [15] and consequently for a representative

soundscape map. In that way, also the objective of equal spatial coverage is satisfied [16].

Emphasising on soundwalks for data collection, the different sampling techniques that can be applied include probabilistic methods, such as random, systematic, stratified or cluster sampling and non-probabilistic or selective methods. The latter comprise various options with purposive, diversity and judgment sampling to be indicated. In particular, diversity sampling is used when it is essential to depict a wide range of values [17].

For a priori designed soundwalks, systematic sampling methods impose a limit on the minimum distances among points; however they can be more accurate than random sampling methods. The latter, offer better representation of the variability, but less representative surfaces [15] in terms of soundscape. On the other hand, diversity sampling is essential when there is a good knowledge of the area and various types of urban spaces or elements of the sound environment are included [18].

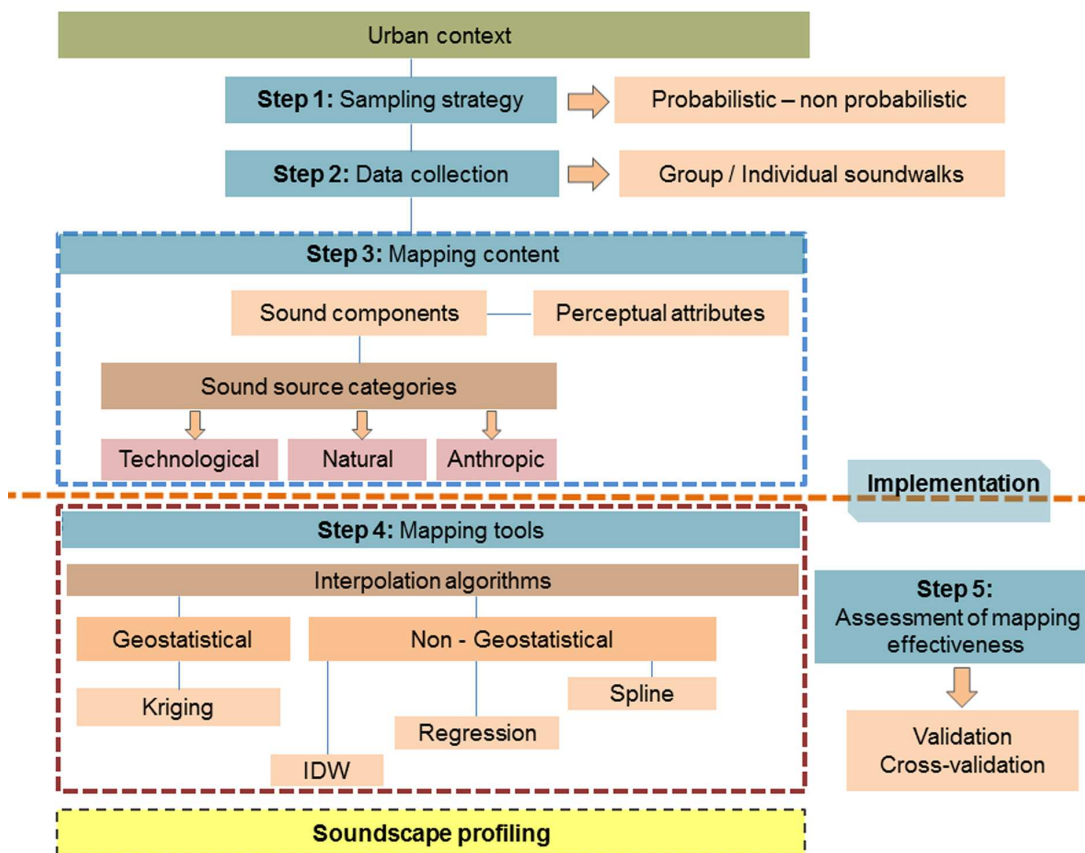


Figure 2: Individual steps in the soundscape mapping process starting from the sampling strategy and ending in the assessment of the mapping effectiveness. Soundscape profiling is an optional step in this process.

2.3 Data collection

Soundwalk methods can be clustered in two clusters. The first one diversifies them according to the time of selecting the measurement points, which varies either before (a priori) or during the measurement period. The second cluster distinguishes soundwalks based on the data collection process from the participants, which can take place either in groups or individually.

Concerning the first cluster, sample points in previous soundwalks were based both on a priori [19–21] and on-site decisions [19, 22] depending on the objectives of the investigation. Both approaches have advantages and disadvantages. In reference to the second cluster, group soundwalks usually include a small amount of points based on a landmark or a specific place attribute; however results can be more robust compared to individual assessment. Biased results can occur, if the study is focused solely on the researchers' intentions by underestimating the participants' experiences [18], which is the primary aim of the soundwalk. On the other hand, individual soundwalks [22] offer

higher number of sampling points; However, they can lead to biased results when locations are chosen in an arbitrary way from the researchers.

2.4 Mapping tools

Soundscape mapping depends on the use of interpolation tools, which can predict cell values in unknown locations based on the cells with known values in the study area. There are various interpolation tools in mapping softwares such as ArcGIS depending on the nature of the phenomena to be modelled. What can be taken for sure is that almost in all cases different interpolation methods will produce different results [23]. Since there are no hard and fast rules for soundscape mapping, previous studies have used several interpolation algorithms such as: Kriging [24, 25] Inverse Distance Weighted (IDW) [26] or Spline [27].

Kriging belongs in the group of geostatistical mapping methods, while IDW and Spline in the group of non-geostatistical interpolation methods. The main ad-

vantages of Kriging compared to the latter group are the use of semivariogram [28], which measures the strength of statistical correlation as a function of distance and also provides an uncertainty estimation. Semivariogram provides the level of spatial smoothing in the predicted values based on the actual observations and the uncertainty is given for the predicted values taking into account the spatial autocorrelation [29].

Despite their differences, spatial interpolation tools comply with some general rules for the expected outcomes. For example, IDW should be used when there is an initial dense set of points, since it can capture the local surface variation. On the other hand, Spline can predict ridges and valleys in the data [23] and is the optimal method for a smooth representation of phenomena such as temperature. Both IDW and Kriging can recognise “warm” and “cold” areas, however, IDW is more deterministic and more likely to produce “bull’s-eyes” around data location. On the other hand, Kriging assumes a stationary and stochastic approach and provides the user with more options when controlling for the final outcome.

2.5 Mapping content

So far, soundscape mapping in different scales has been perceived as a process of visualizing three main parameters: a) sound sources, b) psychoacoustic parameters and c) perceptual attributes relevant to soundscape quality. In particular, previous studies for mapping the variability of sound sources [14, 30, 31] and use various geostatistical and non-geostatistical mapping techniques. A few studies have dealt with the representation of psychoacoustic parameters [26, 32] such as loudness, sharpness or pleasantness in the urban environments. However, very few studies [24, 33] have dealt with the overall assessment of the sound environment as a holistic process and in cooperation with the local planning authorities or City Councils.

2.6 Assessment of mapping effectiveness

The evaluation of the interpolation results and the performance of the model in unknown locations can be performed using the validation or the cross-validation process. Both processes work under the same concept by consecutively removing one or more data points and predicting the respective values using the remaining data entries [34]. This method can assess the quality of the model and compare different models until to find the optimal one, which best fits with the error diagnostic criteria. The

degree of bias and uncertainty that makes a prediction successful is automatically assessed in the cross-validation process using the Geostatistical Wizard to run the interpolation. The conditions that should be met in both cases are presented in Table 1 below:

Table 1: Error diagnostics during the cross-validation process in Kriging interpolation.

Prediction errors	Optimisation target
<i>Bias assessment</i>	
Mean Prediction Error (MPE)	MPE → 0
Mean Standardised Error (MSE)	MSE → 0
Root Mean Squared Prediction Error (RMSPE)	RMSPE → min
<i>Uncertainty assessment</i>	
Average Standard Error (ASE)	ASE ≈ RMSPE
Root Mean Square Standardised Error (RMSSE)	RMSSE ≈ 1

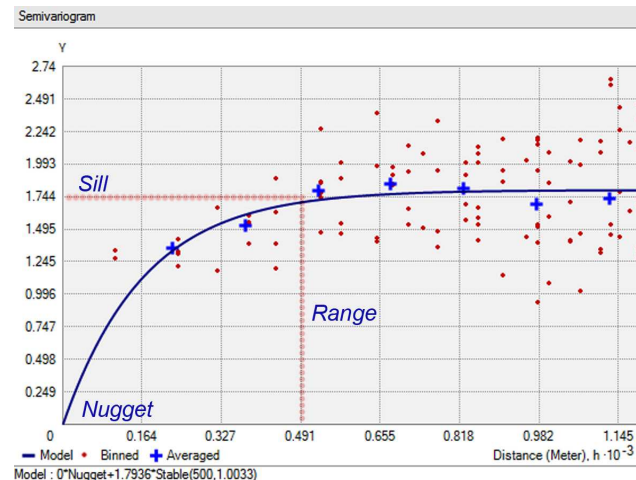


Figure 3: Typical example of semivariogram with the basic components of nugget, range and sill. The red dots represent groups of points (bins) within the lag distance.

In the first case, the bias assessment can give an insight on how close are the predicted values to the true values. In unbiased models the MPE and the MSE should be very close to zero with a minimum RMSPE. In the second case, the uncertainty assessment measures the prediction standard errors so as to estimate the correct variability. When the ASE is similar to the RMSPE, the variability is correctly assessed. In different cases it is either underesti-

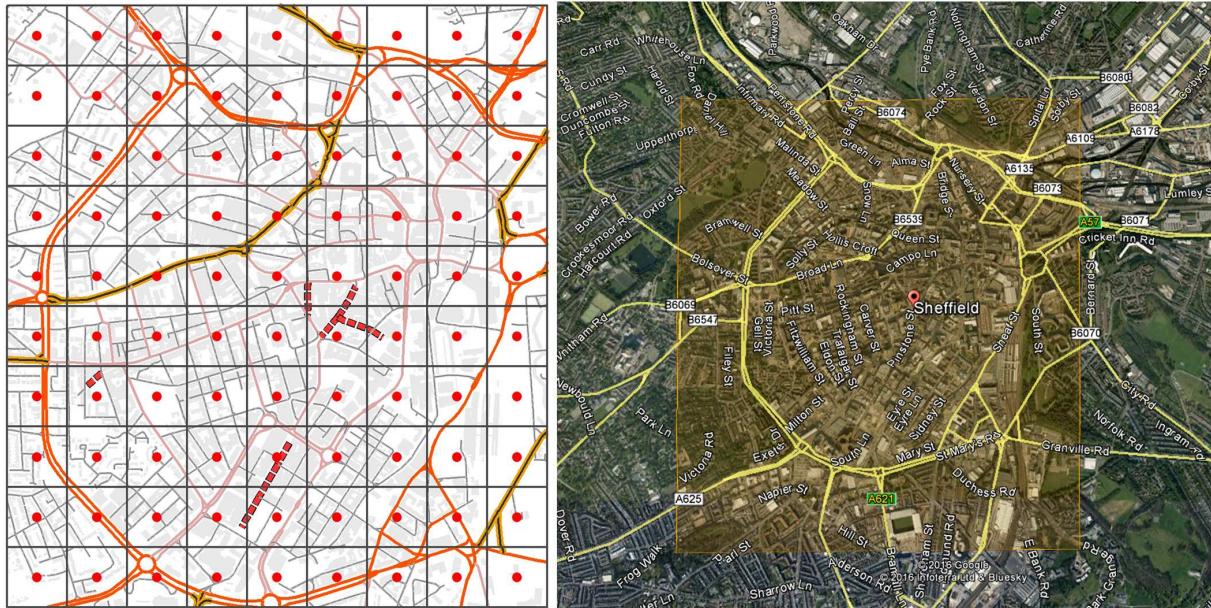


Figure 4: Representation of the study area in Sheffield with the 90 measurement points and the applied grid (200×200) meters.

imated ($ASE < RMSPE$) or overestimated ($ASE > RMSPE$). Finally, similar values in these two error indices can evoke optimal values close to “1” for the RMSSE (Table 1).

Finally, it is worth mentioning the role of the semivariogram in the cross-validation process. The semivariogram, as shown in Figure 3, practically provides a graphic representation of the spatial correlation of the data points and their neighbours. The distances between pairs at which the variogram is calculated are called lags. Then, the lag size is the maximum distance into which pairs of points are grouped in order to reduce the large number of possible combinations. The nugget represents the small scale variability of the data and a small part of the error represented in the y-axis. The range represents the distance over which pairs of points are not spatially correlated. Lastly, the sill represents the maximum detected variability between pairs of points.

3 Model development for sound source maps

In the current case study, cities of Sheffield and Brighton are compared following the methodology, which refers to the two soundwalk approaches as explained in Section 2.3. In particular, the data in Sheffield was collected based on an individual assessment by a single person, while in

Brighton a group soundwalk was followed with an a priori consideration of the selected points.

3.1 Case study site

The study area in Sheffield covers the inner city centre, since it combines many different land use characteristics and can also be considered a typical example of a post-industrial average-sized European city. Furthermore, the area is characterised by a dense and varied network of local and national level of streets as well as transport infrastructures (e.g. railway, tram, buses). The total area extends to 3.6 km². A grid of 200 × 200m was implemented, segregating the region in 90 tiles as it can be seen in Figure 4. The measurement points were defined using a systematic sampling method with a fixed distance interval of 200 meters from one measurement point to the other. Since the first point corresponds to the tile centroid all the following points refer also to centroids. In this way, a smooth and accurate prediction surface was created compared to a random sampling method [35]. In case a centroid resulted to be non-accessible due to legal or physical obstacles (e.g. buildings), the closest publicly accessible point was selected.

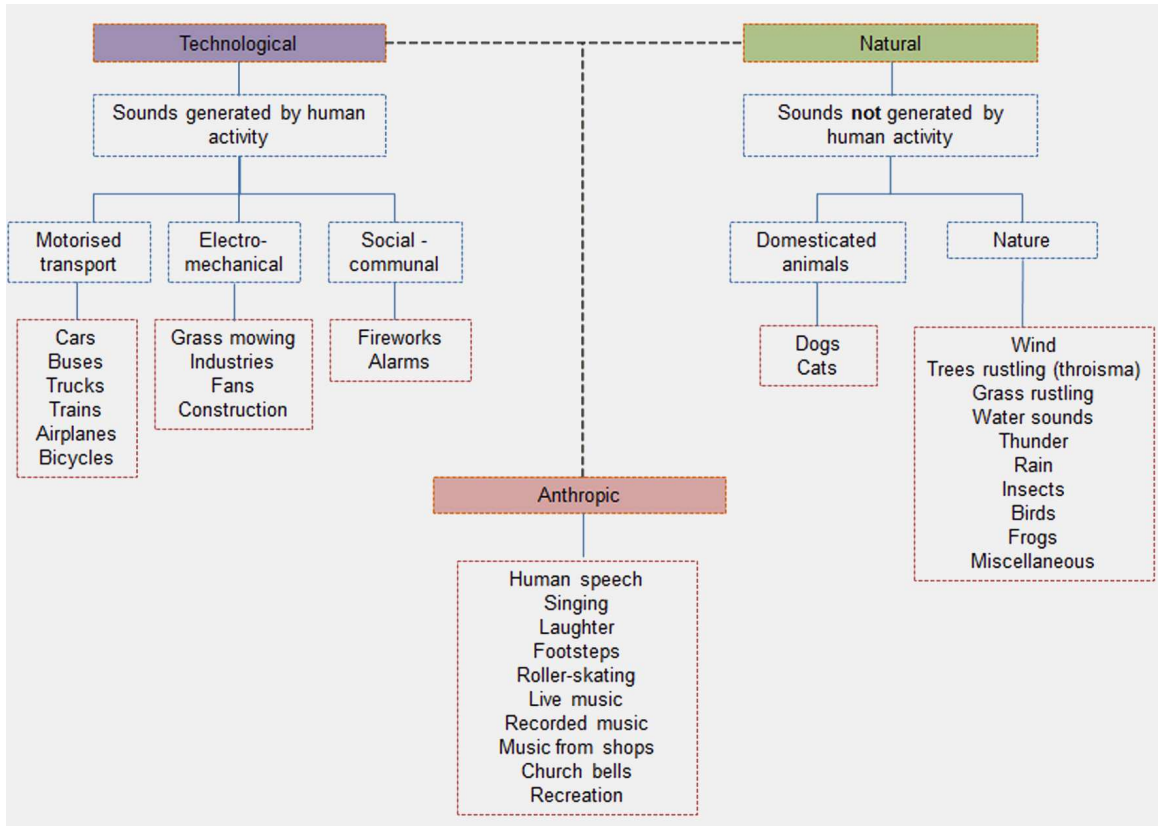


Figure 5: Three main types of sound sources with subcategories used during the measurement campaign. The classification taxonomy follows the suggested paradigm of [36].

3.2 Data collection

Initially, a researcher performed daily measurements in all the 90 centroids (Figure 2) for four working weeks. The measurement period was divided in two time slots: morning (09:00-12:00) and afternoon (14:00-17:00). 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. The “*Audiotool*” Android application was installed on a mobile phone with the microphone MicW i436 attached. This application was used to record the sound pressure levels at each location. The final L_{Aeq} levels per spot were the average levels of both measurement sessions (morning-evening). During this time period the researcher had to mark the number of audible sound sources at each point by checking a form with multiple options as shown in Figure 5. All sound sources were divided in three general groups (“Technological”, “Natural”, “Anthropic”) and further subdivided in subcategories according to the taxonomy followed by [36] for soundscape studies.

3.3 Mapping tools

After the data collection was finalised, all the information related to the audible sound sources was transferred in the ArcGIS software (v.10.1) for further processing. The audible sources’ occurrences were aggregated per type and these values were averaged over morning and afternoon ($Technological_{AVG} = 5$, $Natural_{AVG} = 5$, $Anthropic_{AVG} = 5.5$). Then a prediction surface was created using the Kriging interpolation method for the technological, natural and anthropic sound sources accordingly. The surfaces were created based on the Ordinary Kriging method and the spherical semivariogram model, considering all the 90 points of the study area.

3.4 Mapping content

Three soundscape maps were created for the study area. Figure 6 shows the spatial variability of audible technological, anthropic and natural sound sources respectively. As it can be seen in Figure 6a, areas on top left side - mainly covered by University buildings, parks and resi-

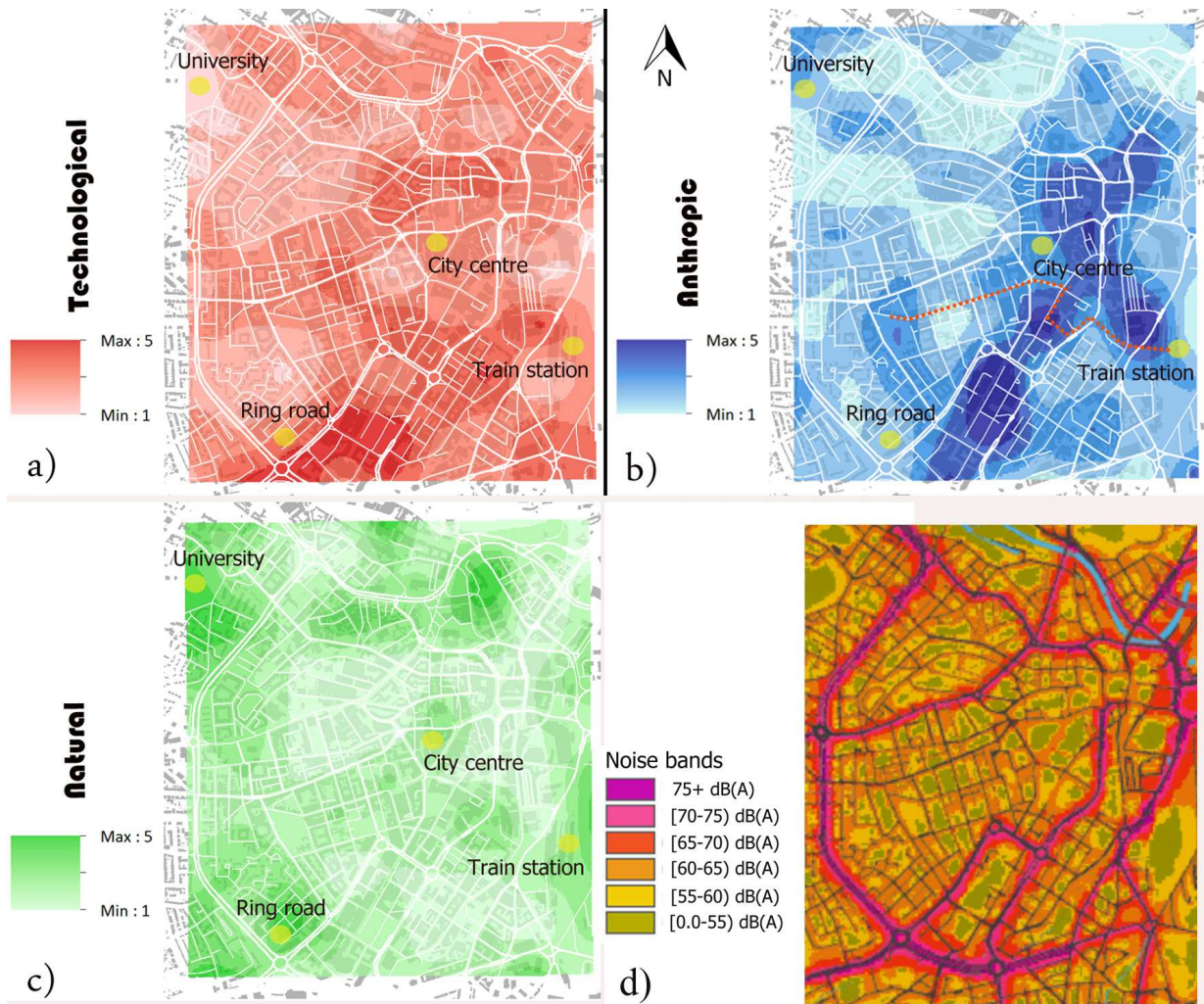


Figure 6: Spatial variability of the audible sound sources (technological, anthropic, natural) in comparison with the corresponding noise map (DEFRA) for the area from the first round of noise mapping.

Table 2: Error diagnostics using the cross-validation process for the sound sources.

Conditions	Errors	Anthropic	Natural	Technological
MPE → 0	MPE	0.011	-0.025	0.005
MSE → 0	MSE	0.010	-0.019	0.005
RMSPE → min	RMSPE	1.200	1.182	0.941
ASE = RMSPE	ASE	1.170	1.182	0.890
RMSSE ≈ 1	RMSSE	1.030	1.000	1.050

dencies - present low levels of technological sources. The same happens in the site above the Ring Road A61, which is a purely residential area. Low technological sources were also present in the right side close to the train station, since it is a space with many natural elements. Similarly, another site with low levels of technological sounds can be identified around the city centre, where pedestrian streets prevail. On the other hand, high concentration of techno-

logical sources was observed in the roundabouts of the Ring Road in St. Mary's Gate and along the main streets in the central zone of the study area. The highest number of technological sources was observed in the southern part, which was expected, since it is the main entrance to the city centre and also combines light industrial and commercial activities.

Anthropic sources presented in Figure 6b, can provide a very representative idea of Sheffield city centre. They create a corridor from the North, where Park Square and river Don are placed, up to the South, where the Moor market is located. Along this line there are many commercial activities, services, entertaining activities and active social life during the greatest part of the day. Evident high values of anthropic presence can be seen also around the area of the train station. This area is partly common with the famous “gold route” of fountain stops around the city [37] and is expected to attract more people as it is very friendly - designed for pedestrians. The presence of human sources is limited on the rest of the study area and especially on the south close to the ring road. What is interesting is the extensive degree of intersection between the high values of “anthropic” and “technological” sources, which can be justified by the commercial character of the area.

Then, in Figure 6c it can be seen that increased number of natural sources is evident in specific areas around the ring road which constitutes parks, exclusive residential areas or places close to river Don on the North. The West side of the study area is more privileged in terms of natural sounds, because of the proximity to urban green spaces and playgrounds, while the house type with backyards or front yards enhances the presence of birds and small animals. The city centre presents the lowest aggregation of natural sounds with a small presence in various squares. It is also surprising that most of these places are along the main highway creating a contradictory soundscape environment with increased number of technological and natural sources very close to each other.

Another point to consider is the comparison between the noise map of Sheffield city centre as shown in Figure 6d and the sound sources maps. There are expected similarities between the representation of technological sources (Figure 6a) and the traffic noise levels in the noise map. However, there is an extra source of information that refers to natural and anthropic sources, which cannot be represented in the noise maps. Complementary characteristics like those constitute a positive example of soundscape planning with further perspectives in the planning or design process.

3.5 Mapping effectiveness and implementation

As discussed in Section 2.6 it is important to know the model’s performance after implementing the interpolation. For the above sound source maps the effectiveness was assessed using the Geostatistical Wizard and the

cross-validation process. The optimal fit of the semivariogram model was achieved using a lag size of 200 meters in accordance with the grid size. This approach is also supported by Isaak & Srivastava (1990) for areas where the samples follow a (pseudo) regular grid. The number of lags was kept to 12 and the nugget was adjusted to 500 meters. The final results of the cross-validation process can be seen in Table 2.

The model presented small error values in all the three sound source categories with the best performance to be presented in the technological sources. Overall, the predicted values were close to the measured ones with the highest errors to be present only in the extreme cases of outlier measurements either close to 0 or close to 6 in a six-point scale. Finally, the fact that the ASE was lower than the RMSPE in all cases provides evidence that the variability was slightly underestimated.

3.6 Soundscape profiling

A step forward after the cores five steps that are included in the proposed framework (see Figure 2) the visualisation of the sound sources variability as presented above was the identification of possible profiles, which would provide further information on the character of the area. The analysis was performed on the initial grid level of 200×200 meters and the individual steps towards the profile creation are described below.

Initially, the values for all sound sources in every measurement point were standardised to range between (-2) and $(+2)$ using integer numbers. Afterwards, the minimum and maximum values were selected for each sound source in order to create the “High” (H) and “Low” (L) profiles. All the (H) represent cases where the value for each sound source in the respective tile is equal to $(+2)$. Correspondingly, the (L) values represent cases where the value for each sound source in the tile is equal to (-2) . Based on the three sound source categories a maximum combination of eight pairs was formed as presented in Figure 7.

The first group includes three classes and refers to grids with maximum values for technological sources, classified as “High Technological”. The second group refers to profiles with maximum values for natural sources, classified as “High Natural”. Then, the next group with a single profile was classified as “High Anthropic” due to the maximum levels detected in the respective sound source. Finally, the last profile with minimum values in all sound sources (grey colour) was left out as an outlier in the current analysis with no need for further classification.

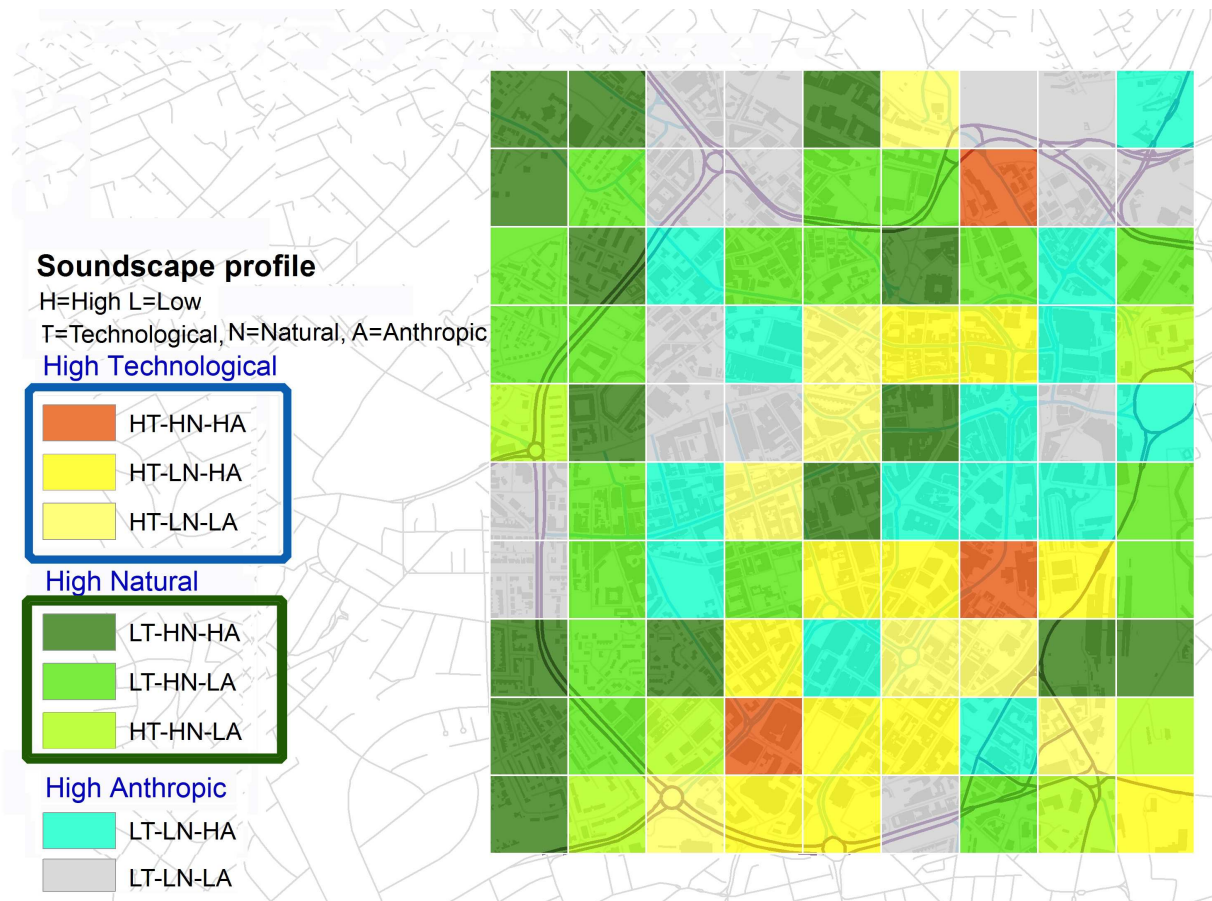


Figure 7: Representation of the eight “High” (H) and “Low” (L) profiles of the sound sources and arranging them into three larger groups based on the maximum levels per sound source within the study area.

It was found that the majority of the tiles (43%) belong in the “High Natural” profiles showing that there were areas with various natural sources that outnumbered technological and anthropic sources. These areas were mainly located outside or in the borders of the Ring Road. Another 24% of the tiles represented one of the three combinations in the “High Technological” profile. These places were located either in some central locations close to the city centre or in the middle and southern zone of the case study area, where technological sources are numerous. There were also fourteen tiles (16%) spread in the study area representing a prevalence in anthropic sources. These tiles were distributed in residential areas close to the left side of the A61, on the western side of the Ring Road, the pedestrian areas of the city centre, the Moor market area and close to the train station. Finally, 17% of the total area was covered by tiles characterised by the minimum score in all sound sources. These places were mainly located in the northern part of the study area around the Ring Road, covering old industrial sites or areas close to river Don. Similar places were identified in mixed educational and tertiary

service zones close to University premises, presenting low noise variability during the measurement period.

4 Model development for soundscape maps

A first conclusion that can be drawn from the literature review is the lack of studies in the field of soundscape mapping compared to noise mapping. As [31] mention, one possible reason is the absence of objective data to generate such maps compared to noise maps. Previous works in this field refer to the spatial representation of loudness and soundscape quality [26, 32], or the soundscape ecology in parks [27] and rural areas [38]. As expected, the majority of these studies are disconnected from the planning process or present the potential to be integrated in this field. Apart from the current study, also [11] and [24] made an attempt to bridge this gap in cooperation with local City Councils or planning authorities.

4.1 Case study site

The test site of this model is placed in the city centre of Brighton & Hove (UK). It corresponds to the Valley Gardens area and extends from the seafront roundabout (Brighton dock) up to 1.5 km into the city. The site is a key access point for entering and leaving the city and also for accessing the seaside; consequently it is substantially affected by high noise levels from traffic. Overall, the green areas within the site are currently used by the residents only as a transition point and not for their leisure activities. Within the study area, eight locations were selected as shown in Figure 8, namely: the Seafront (1), the Old Steine (2), the Royal Pavilion (3), the statue in Victoria Gardens South (4), the Mazda Fountain in Victoria Gardens South (5), Victoria Gardens North (6), St. Peter's Church (7) and the Level (8). The concept for selecting such places was to provide a sufficient variability of different urban contexts and corresponding acoustic environments within the study area.

The current study refers to the assessment of the present condition of the acoustic environment before any intervention. Key areas for the next stage include specific measures towards noise absorption or masking interventions and the provision of positive soundscape elements.

4.2 Data collection

Twenty-one people between 25 and 68 years old, participated in the soundwalk (16 men; 5 women, $Age_{AVG} = 38.7$ years, $SD = 11.5$). The soundwalk took place during a week day (Monday morning) from 09:30 am to 10:30 am. The researchers led the participants by walking through the study area and making stops at the eight selected locations. The basis for selecting eight points was to provide the participants with a relatively limited number of spots that were able to inform them about the overall sound environment of the site. This is in line with conventional group soundwalk methods [19].

For each location, participants were asked to listen to the sonic environment for a period of two minutes and fill in a structured questionnaire. The current research refers to the question: “For each of the eight scales below, to what extent do you agree or disagree that the present surrounding sound environment is...”. In all cases, a scale of no fixed answers was used in order to avoid bias or rounded answers. Participants had to put in a mark on a 10-cm continuous scale assessing eight perceptual attributes namely: “pleasant”, “chaotic”, “exciting”, “uneventful”, “calm”, “unpleasant”, “eventful” and “monotonous” following

the soundscape model suggested by [39]. The marking scale ranged from “strongly disagree” to “strongly agree”.

4.3 Mapping tools

A different approach for the characterization of the sound environment was applied in Brighton. In contrast to Sheffield, the data collection for this city was based on a 60min-group soundwalk, emphasizing more on perceptual characteristics and not on sound sources. Also the soundscape protocol that was followed in this case was different as described in detail in Section 4.2. The input data for the current implementation in Brighton were based on the mean values of the individual responses provided by the 21 people who assessed the perceptual attributes and sound sources' profiles throughout the area. Specifically, the mean values of the attributes: “pleasant”, “calm”, “uneventful”, “monotonous”, “unpleasant”, “chaotic”, “eventful” and “exciting” were used as input variables for the Kriging interpolation method in order to produce the corresponding prediction maps using the Spatial Analyst tool in ArcGIS. The analysis was performed using the Ordinary Kriging, which assumes a stationary and stochastic approach with a constant mean value and random errors. The degree of spatial autocorrelation among the data was assessed by the semivariogram. In this case a spherical semivariogram was selected, since there were no directional effects among the eight sample points.

4.4 Mapping content

The spatial distribution of perceptual attributes in the study area was visualised using a colour ramp as depicted in Figure 9. It ranges from 0 to 10, following the ten-point scale of the soundwalk questionnaire. For graphical purposes the colour ramp consists of 20 colours, each representing a 0.5 step in the ten-point scale. In that way all maps were rendered comparable to each other with graphically visible variations. It is worth noting that interpolation processes do not take into account the physics of sound propagation such as reflections from ground or buildings nor the actual sound distribution. They rather aim at mapping a likely distribution of sound's perception by interpolating aggregated individual assessments over a set of discrete points.

The perceptual attributes can be better described by comparing two groups. The first one includes the reference points 3 and 8, while the second group comprises the rest of the places. In total, six out of the eight perceptual at-

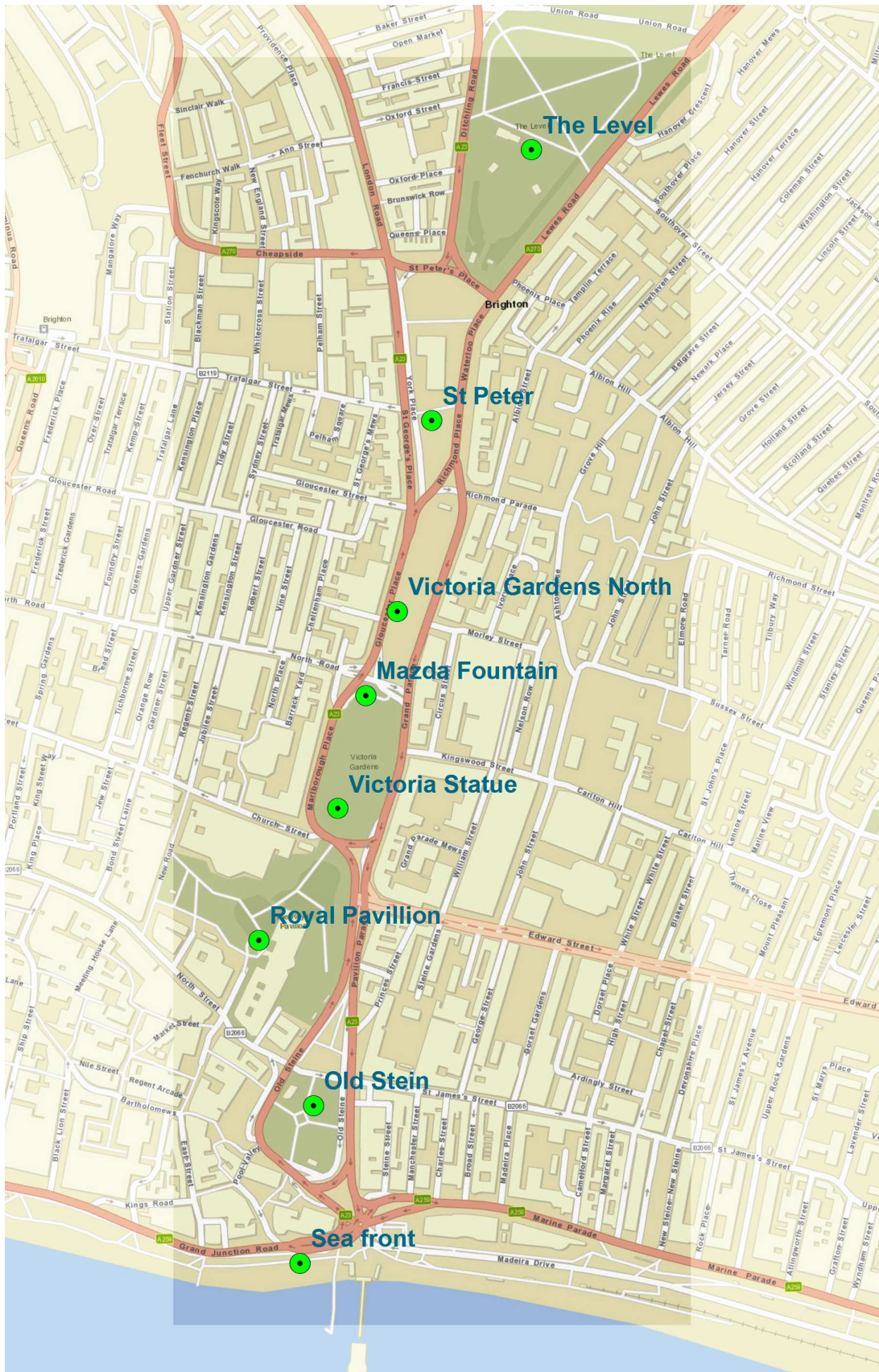


Figure 8: The eight locations selected for the soundwalk and the binaural recordings using the ESRI World Street Basemap.

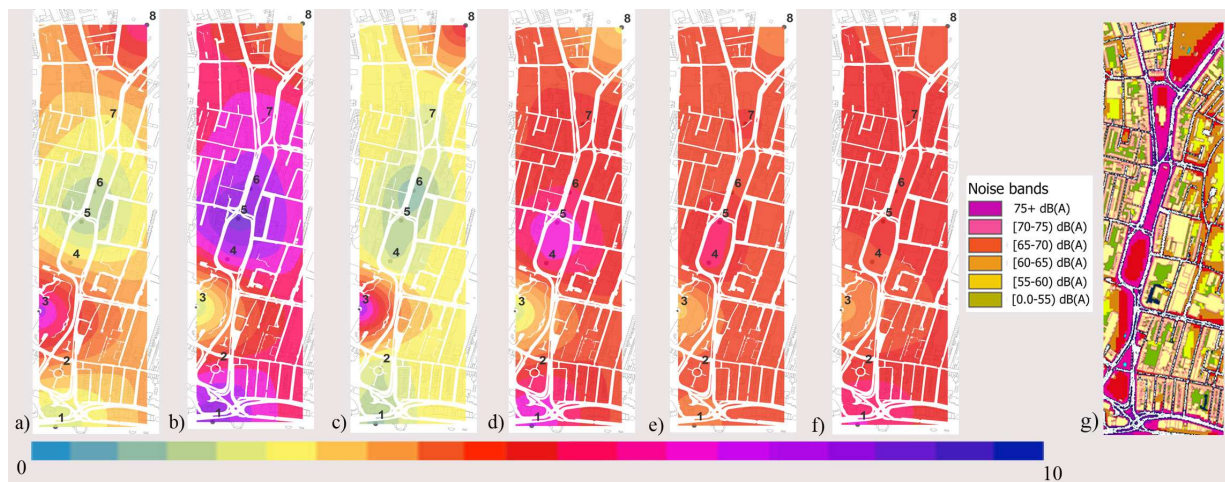


Figure 9: Range of perceptual attributes in the study area using a 0-10 scale depicting a) pleasant, b) unpleasant, c) calm, d) chaotic, e) eventful, f) monotonous and (g) the official first round noise map (DEFRA).

tributes were represented and analysed, since the values for ‘vibrant’ and ‘uneventful’ were not spatially autocorrelated.

Overall, the entire area in Figure 9a was poorly characterised as ‘pleasant’ with a low area average ($M_{1-8} = 3.5$) and values ranging between 1.6 and 6.8. Points 3 ($M=6.8$) and 8 ($M=6.1$) were identified as the most pleasant places in the entire site, while points 5 ($M=1.6$) and 6 ($M=1.6$) as the least pleasant. The attribute ‘unpleasant’ in Figure 9b ranged from 1.9 to 7.8 with values above the area average ($M_{1-8} = 5.8$) among all the attributes. Chaotic in Figure 9d follows also the same pattern with slightly lower levels ranging from 2.0 to 6.6 and an area average of $M_{1-8} = 5.0$. The attribute ‘calm’ in Figure 9c ranged from 1.0 to 7.2 presenting the highest variation ($SD_{1-8} = 2.28$) and the lowest mean value in the area ($M_{1-8} = 2.8$). The lack of calmness was mostly evident in points 1 and 6. Generally, ‘calm’ followed the same pattern as ‘pleasant’ with slightly lower levels in all the positions. In point 3 both parameters had their maximum ($M=7.2$ and $M=6.8$, respectively), possibly enhanced by the sense of enclosure provided by the trees in that location.

The attributes ‘eventful’ and ‘monotonous’ (Figures 9e,9f) presented the lowest variation in the area, respectively ($SD_{1-8} = 0.86$, $SD_{1-8} = 0.72$), with no significant peaks or lows and levels close to 5.0. Points 4 and 5 were the only ones characterised as slightly more ‘eventful’ than ‘monotonous’, while point 3 was characterized as the least eventful and monotonous in the entire area. However, low variation in these two attributes is not necessarily a negative characteristic as it can provide a general picture for the whole area, which is deprived of a particular sonic identity due to the vulnerability to traffic noise.

It can also be seen that there are similarities and differences between the maps of perceptual attributes and the noise map of the study area as shown in Figure 9g. In particular, there is a correspondence in the areas that were rated as “unpleasant” and the areas with high noise levels. Nevertheless, areas that were rated as “pleasant” or “calm” in the perceptual maps (points 3,8) are still represented in a high noise band in the noise map. This comparison can be used as an evidence to show the complementary nature of objective and subjective attributes of the outdoor sonic environment.

Overall, the current appraisal of the sound environment in the area was mostly negative, except for points 3 and 8. High traffic volumes around the park had a negative impact with the situation to be aggravated by the linear shape of the Valley Gardens and the absence of enclosure features of green infrastructure. Future intervention should target at the increase of “pleasantness” and “calmness” in the area, connecting the natural elements of the seafront - which also received negative assessments (chaotic, unpleasant, and monotonous) - with an improved land use and network structure.

4.5 Mapping effectiveness and implementation

In the last stage of the GIS implementation, a cross-validation process was used to evaluate the performance of the interpolation in ArcGIS. According to the results of Table 3, it can be seen that most of the conditions were met to a great extent, making sure that the predictions are centred to the true values and have a low uncertainty.

Table 3: Error diagnostics using the cross-validation process for the perceptual attributes.

Conditions	Errors	Pleasant	Unpleasant	Calm	Chaotic	Eventful	Monotonous
MPE → 0	MPE	-0.27	0.22	-0.23	0.16	0.13	0.01
MSE → 0	MSE	-0.08	0.07	-0.07	0.06	0.10	-0.01
RMSPE → min	RMSPE	1.92	2.26	2.61	1.93	0.96	0.77
ASE ≈ RMSPE	ASE	2.02	2.25	2.48	1.80	0.97	0.75
RMSSE ≈ 1	RMSSE	0.90	0.98	1.03	1.05	0.99	1.00

In particular the Mean Prediction Error (*MPE*) and the Mean Standardised Error (*MSE*) were very close to zero ($\max_{MPE} = -0.27$, $\max_{MSE} = 0.10$). A small underestimation in the variability of the predictions was evident, since the Root Mean Square Prediction Error (*RMSPE*) was slightly higher than the Average Standardized Error (*ASE*) in four out of six cases, with a maximum difference of 0.13 in “unpleasant” and “calm”. Definitely, a lower *RMSPE* ($\max=2.61$) would have been achieved if some extra points would have been included between points 3 and 4 as well as between points 7 and 8. Nevertheless, the current results suggest that the sample size was sufficient for the purposes of this analysis. On the top of that, all points - apart from the reference ones - were uniformly distributed so as to have an objective description of the area.

4.6 Soundscape profiling

One of the main assets in the above soundscape maps and overall in the field of interpolation is the ability to apply more complex and combined queries retrieving the areas, which satisfy specific criteria. For instance, using the “extract by attributes” tool in ArcGIS it is feasible to represent such areas. Figure 10 depicts a characteristic example of the potential queries that can be built. Areas in points 3 and 8 represent cases, which were rated as “calm” and “pleasant” with a score above 5 / 7.5. On the other hand, areas in the rest of the points correspond to places characterised as “chaotic” and “annoying” with a score higher than 5 in a scale from 1 to 8.

This kind of combinations can give a more detailed picture of the current condition of the acoustic environment. Hence, the local City Councils or the planning authorities have a tool to assess the current soundscape quality of the study area and design the future interventions according to a particular acoustic strategy as presented in Figure 1.

5 Discussion

5.1 Model effectiveness

As regards the model effectiveness in Sheffield, small error values in all the three sound source categories were found with the most accurate and unbiased interpolation to be presented in the technological sources (Table 2). Overall, the predicted values per point were close to the measured ones with the highest errors (+2.5) to be present only in outlier values during the soundwalk. In Brighton soundwalk the interpolation model had an optimal performance for the “monotonous” perceptual variable with very low error values. On the other hand, the highest errors (*RMSPE* = 2.61, *ASE*=2.48) were detected for “calm” and “unpleasant” (*RMSPE* = 2.26, *ASE*=2.25). Overall, it was shown that a geo-statistical model such as Kriging can be applied successfully in soundscape mapping with unbiased models both in the small scale mapping - where parks or squares are considered - and in the large scale of a typical city centre.

The accuracy in soundscape mapping as presented in the results section for both case studies depends on various parameters. The most crucial include the size of the area, the number of points measured as well as their spatial distribution and the way of selecting them (a priori, on site). Although the use of spatial interpolation methods has not been always successful in the prediction of noise levels [25] it has been shown that they can be useful for mapping soundscape quality or particular perceptual attributes in the urban context [24, 26]. Definitely the proper soundscape data collection method should be applied according to the scope of the study. Moreover, in terms of sampling strategy, purposive (non-probability) sampling is generally considered more efficient than probability sampling [40]. However, systematic sampling seems to be an option that provides more representative results compared in larger areas.

In terms of mapping content, for parks or rural areas, a suitable categorization of sound sources can follow the example of [38] or [27] which is nature-oriented (anthropophony, biophony, geophony). Nonetheless, for ur-

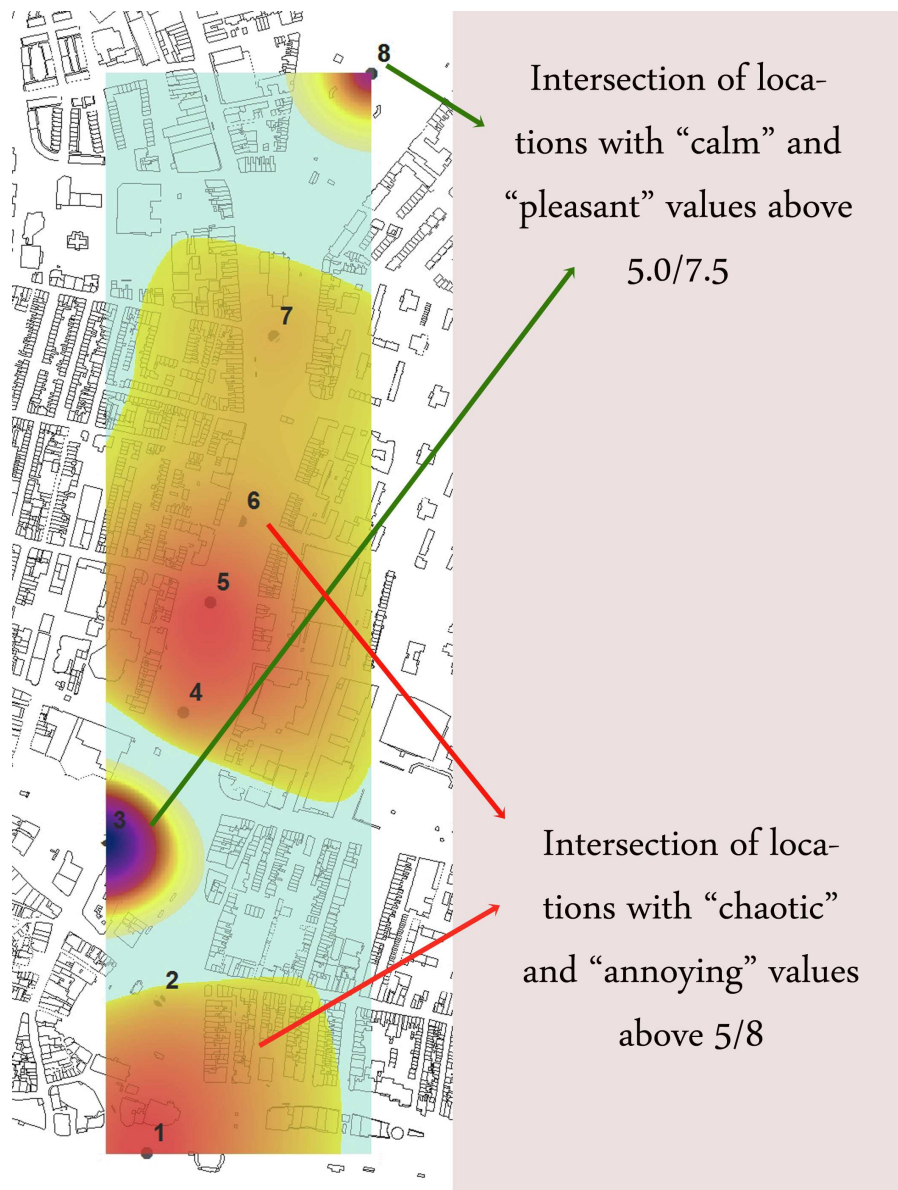


Figure 10: Spatial queries with combined results contributing to the recognition of calm/pleasant areas (points 3,8) and chaotic/annoying areas (points 1,2,4-7).

ban environments a categorization that can be more representative is closer to the taxonomy of human, natural and technological sources previously used in other studies as well [32, 41, 42].

5.2 Implementation - advantages of soundscape mapping and complementarities with noise maps

Concerning the advantages of soundscape mapping in the implementation stage, according to the described frame-

work, there are two main points worthwhile to be mentioned. The first one refers to the data collection step and the other one in the profiling stage. The individual data collection method in Sheffield - highlighted also by [18] - is the appropriateness of this method for broad areas with flexibility in assessments at diverse times and days [43]. Typically, traditional soundwalks are fulfilled in one day with limited duration between 10' [44] and 90' [21]. Another asset is the extensive noise variability with a large dataset, which helps to create a smoother interpolation surface with equal coverage.

In the profiling stage, the group soundwalk method applied in Brighton and the quantification of perceptual attributes visualized in Valley Gardens offers the chance to recognize areas that needed to be acoustically improved or were already quiet. It was proved that there were critical areas in the noise maps classified in high noise bands, but characterized as “calm” during the soundwalk. This can partly be explained by factors, which cannot be taken into account in noise mapping, such as the masking effect of traffic by other sources such as birdsongs [45] and the dense vegetation in the area. The advantage of the group soundwalk method is the provision of more representative results as all spots are assessed by a group of people, so they tend to be more popular according to the latest studies [20, 22, 24]. However, the short-term duration of listening in every spot can only capture a small fraction of the dynamic and temporal pattern of urban soundscapes compared to individual soundwalks.

6 Conclusions

The aim of this study was primarily to develop a mapping model to aid soundscape planning and secondly to assess its effectiveness. After the entire process a framework for soundscape mapping was established based on specific steps and flexible to handle with different input data.

- Firstly, a sound source mapping technique was established using a probabilistic sampling strategy and an individual data collection method combined with Ordinary Kriging interpolation technique. The model was based on input data from the initial classification of sound sources. The prediction map of the study area displayed that areas close to University buildings, parks and residential sites - well protected from green belts - presented low technological sources. On the contrary, high concentration of the same sources was evident - as expected - in congested roundabouts around the Ring Road and along the main roads towards and around the city centre.

A high number of natural sources was evident close to parks, exclusive residential areas and other places with a high degree of naturalness, such as districts close to the river. The presence of natural sounds was also enhanced in areas, where the housing type included vegetated backyards or front yards. Finally, an unexpected high number of natural sounds were recorded in areas close to the Ring Road with the co-existence of technological and natural sources.

Anthropic sources were mainly evident in proximity to natural elements such as parks or water features, since they provide a source of relaxation and restoration. Then, a high number of anthropic sources was also detected close to the main market and in proximity to commercial and social activities. These results do not account for sound source intensity, since the main aim was to capture the plethora and the number of different sources.

- Secondly, a perceptual soundscape mapping technique was established using a purposive sampling strategy. A group data collection soundwalk method was applied using the geostatistical Ordinary Kriging interpolation technique. The model was based on input data from perceptual attributes collected in Valley Gardens, Brighton. It was found that the overall appraisal of the sound environment in the area was mostly negative, except for points 3 and 8, which were the most pleasant. High traffic volumes around the park had a negative impact on the listener’s perception with the situation to be aggravated possibly by the absence of enclosure features of green infrastructure.

In terms of profiling, it was found that out of the 90 tiles in Sheffield the majority of them (43%) belonged in the profile where natural source prevailed. Technological sources dominated in 24% of the tiles and another 16% of the tiles was characterised by the high presence of anthropic sources. The profiling in Brighton case study was based on combined query satisfaction of specific attributes, such as “calm-pleasant” and “chaotic-annoying”. More criteria and queries can be applied depending on the purpose of the analysis and the acoustic objectives that should be met. Generally, the outcome from both case studies was that the proposed soundscape framework can be applied in environmental noise management and the soundscape planning process in different urban scales.

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References

- [1] Directive 2002/49/EC of the European Parliament relating to the assessment and management of environmental noise. Brussels: Publications Office of the European Union, <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32002L0049>
- [2] Environmental Protection Agency, Guidance Note for Strategic Noise Mapping for the Environmental Noise Regulations 2006, 2nd version, 2011
- [3] Kang, J. and Schulte-Fortkamp, B., *Soundscape and the built environment* (1st ed.). Miami, USA: CRS Press, Taylor and Francis Group, 2015
- [4] Szczodrak, M., Kotus, J., Kostek, B. and Czyżewski, A., Creating dynamic maps of noise threat using PL-grid infrastructure. *Arch. Acoust.*, 2013, 38, 235–242
- [5] Wei, W., Van Renterghem, T., De Coensel, B. and Botteldooren, D., Dynamic noise mapping: A map-based interpolation between noise measurements with high temporal resolution. *Appl. Acoust.*, 2016, 101, 127–140
- [6] D’Hondt, E., Stevens, M. and Jacobs, A., Participatory noise mapping works! An evaluation of participatory sensing as an alternative to standard techniques for environmental monitoring. *Pervasive Mob. Comput.*, 2013, 9, 681–694
- [7] Guillaume, G., Can, A., Petit, G., Fortin, N., Palominos, S., Gauvreau, B., et al., Noise mapping based on participative measurements. *Noise Mapp.*, 2016, 3, 140–156
- [8] European Environment Agency-Technical Report. Good practice guide on quiet areas., 2014, http://eionet.kormany.hu/download/4/52/b0000/Tech_04_2014_Guide_on_quiet_areas_high_res.pdf
- [9] Kang, J., A systematic approach towards intentionally planning and designing soundscape in urban open public spaces, Proceedings of Internoise Conference, Global Approaches to Noise Control (28-31 August, 2007, Istanbul, Turkey)
- [10] Easteal, M., Bannister, S., Kang, J., Aletta, F., Lavia, L. and Witchel, H., Urban sound planning in Brighton and Hove, Proceedings of Forum Acusticum, (7-12 September, 2014, Krakow, Poland)
- [11] Alves, S., Estévez-Mauriz, L., Aletta, F., Echevarria-Sanchez, G. and Virginia Puanna, R., Towards the integration of urban sound planning in urban development processes : the study of four test sites within the SONORUS project. *Noise Mapp.*, 2015, 2, 57–85
- [12] Adams, M. D., Davies, W. J. and Bruce, N. S., Soundscapes: an urban planning process map, Proceedings of Inter-noise Conference (23-26 August, 2009, Ottawa, Canada)
- [13] De Coensel, B., Bockstaal, A., Dekoninck, L., Botteldooren, D., Schulte-Fortkamp, B., Kang et al., The soundscape approach for early stage urban planning: a case study, Proceedings of Inter-noise Conference (13-16 June, 2010, Lisbon, Portugal)
- [14] Margaritis, E., Aletta, F., Axelsson, Ö., Kang, J., Botteldooren, D. and Singh, R., 2015. Soundscape mapping in the urban context: a case study in Sheffield, Proceedings of AESOP Conference (13-16 July, 2015, Prague, Czech Republic), 962–974
- [15] Negreiros, J., Painho, M., Aguilar, F. and Aguilar, M., Geographical information systems principles of ordinary kriging interpolator, 2010, *J. Appl. Sci.*, 2010, 10, 852-867
- [16] Wang, J. F., Stein, A., Gao, B. B. and Ge, Y., A review of spatial sampling. *Spat. Stat.*, 2012, 2, 1–14
- [17] Derthick, M., Christel, M. G., Hauptmann, A. G. and Wactlar, H. D., Constant density displays using diversity sampling, Proceedings of IEEE Symposium on Information Visualization (19-21 October, 2003, Washington DC, USA)
- [18] Jeon, J.Y., Hong, J.Y. and Lee, P.J., Soundwalk approach to identify urban soundscapes individually. *J. Acoust. Soc. Am.*, 2013, 134, 803–12
- [19] Adams, M., Bruce, N., Davies, W., Cain, R., Jennings, P., Carlyle, A. et al., Soundwalking as a methodology for understanding soundscapes, Proceedings of Institute of Acoustics, 2008, 30, 1–7, <http://usir.salford.ac.uk/2461/>
- [20] Aletta, F., Brambilla, G., Maffei, L. and Masullo, M., Urban soundscapes: characterization of a pedestrian tourist route in Sorrento (Italy), *Urban Sci*, 2016, 1, 1–10
- [21] Nilsson, M.E. and Berglund, B., Soundscape quality in suburban green areas and city parks, *Acta Acust. united with Acust.*, 2006, 92, 903–911
- [22] Jeon, J. Y., Lee, P. J., Hong, J. Y. and Cabrera, D., Non-auditory factors affecting urban soundscape evaluation. *J. Acoust. Soc. Am*, 2011, 130, 3761–70
- [23] Childs, C., Interpolating surfaces in ArcGIS Spatial Analyst. *ArcUser Magazine*. ESRI, 2004, <http://webapps.fundp.ac.be/geotp/SIG/interpolating.pdf>
- [24] Aletta, F. and Kang, J., Soundscape approach integrating noise mapping techniques: a case study in Brighton, UK. *Noise Mapp.*, 2015, 2, 1-12
- [25] Can, A., Dekoninck, L. and Botteldooren, D., Measurement network for urban noise assessment: Comparison of mobile measurements and spatial interpolation approaches. *Appl. Acoust.*, 2014, 83, 32–39
- [26] Hong, J. Y. and Jeon, J. Y., Exploring spatial relationships among soundscape variables in urban areas: A spatial statistical modelling approach, *Landsc. Urban Plan*, 2017, 157, 352–364
- [27] Liu, J., Kang, J., Luo, T., Behm, H. and Coppack, T., Spatiotemporal variability of soundscapes in a multiple functional urban area, *Landsc. Urban Plan.*, 2013, 115, 1–9
- [28] Myers, R., *Classical and modern regression with applications*, 2nd ed., Boston, MA:Duxbury, 1990
- [29] Aalto, J., Pirinen, P., Heikkinen, J. and Venäläinen, A., Spatial interpolation of monthly climate data for Finland: comparing the performance of kriging and generalised additive models. *Theor. Appl. Climatol*, 2013, 112, 99–111
- [30] Aiello, L. M., Schifanella, R., Quercia, D. and Aletta, F., Chatty maps: constructing sound maps of urban areas from social media data. *R. Soc. open sci.*, 2016, 3
- [31] Rodríguez-Manzo, F. E., Garay-Vargas, E., García-Martínez, S., Lancón-Rivera, L. and Ponce-Patrón, D., Moving towards the visualisation of the urban sonic space through soundscape mapping, Proceedings of the ICSV 2015 - 22nd International Congress on Sound and Vibration (12-16 July, 2016, Florence, Italy), 12–16
- [32] Lavandier, C., Aumond, P., Gomez, S. and Dinguès, C., Urban soundscape maps modelled with geo-referenced data. *Noise Mapp.*, 2016, 3, 278–294
- [33] Kropp, W., Forsén, J., & Estévez Mauriz, L. (Eds.), *Urban sound planning – the SONORUS project*, 1st ed., Gothenburg: Chalmers University of Technology, 2016

- [34] Dubrule, O., Cross validation of kriging in a unique neighborhood, *J. Int. Ass. Math. Geol.*, 1983, 15, 687–699
- [35] Griffith, D. and Layne, L., A case book for spatial statistical data analysis. A compilation of analysis of different thematic datasets. New York: Oxford University Press, 1999
- [36] Brown, A.L., Kang, J. and Gjestland, T.. Towards standardization in soundscape preference assessment. *Appl. Acoust.*, 2011, 72, 387–392
- [37] Sheffield City Council., Public realm, the gold route, 2012, <http://www.welcometosheffield.co.uk/content/files/1281/>
- [38] Papadimitriou, K. D., Mazaris, A. D., Kallimanis, A. S. and Pantis, J. D. Cartographic representation of the sonic environment. *Cartogr. J.*, 2009, 46, 126–135
- [39] Axelsson, Ö., Nilsson, M. E. and Berglund, B., A principal components model of soundscape perception. *J. Acoust. Soc. Am.*, 2010, 128, 2836–2846
- [40] de Gruijter, J., Brus, D., Bierkens, M.F. and Knotters, M., Sampling for natural resource monitoring. Springer Berlin Heidelberg, New York, 2006
- [41] Pijanowski, B. C., Villanueva-Rivera, L. J., Dumyahn, S. L., Farina, A., Krause, B. L., Napoletano, B. M. et al., Soundscape ecology: the science of sound in the Landscape, *BioScience*, 2011, 61, 203–216
- [42] Yang, W. and Kang, J., Soundscape and sound preferences in urban squares: a case study in Sheffield. *J. Urban Des.*, 2005, 10, 61–80
- [43] Semidor, C., Listening to a city with the soundwalk method, *Acta Acust. united with Acust.*, 2006, 92, 959–964
- [44] Adams, M., Cox, T., Moore, G., Croxford, B., Refaee, M. and Sharples, S., Sustainable soundscapes: noise policy and the urban experience. *Urban Stud.*, 2006, 43, 2385–2398.
- [45] Hao, Y., Kang, J. and Wörtche, H., Assessment of the masking effects of birdsong on the road traffic noise environment., *J. Acoust. Soc. Am.*, 2016, 140, 978–987