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Auralisation of an Urban Soundscape

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Summary
A novel approach to qualitative soundscape assessment is presented in the form of a *virtual sound walk*. The virtual sound walk method combines acoustic modelling and auralisation techniques with qualitative assessment methodologies from the field of soundscape research. A case study is presented in which the method is used to predict the impact of noise interventions on the perceived sound quality in an urban environment. Prior to the auralisation, a real sound walk is carried out in the case study environment. By comparison of the results from the two sound walks, it is found that the *virtual sound walk* elicits experiences similar to those of the real sound walk. The suitability of the approach for assessing the impact of potential noise treatments is also evaluated and found to have merit, though it is acknowledged that further refinements are needed. It is thought that the virtual sound walk may be able to assist acousticians and urban designers in a practical sense, as well as helping to promote human-environment interaction in other creative applications.

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1. Introduction

Environmental noise is now recognised by the European Union as being 'one of the main local environmental health problems in Europe' [1]. Efforts to control environmental noise typically aim to reduce sound pressure levels (SPLs), either through strategic urban planning or, where preventative methods are ineffective, by taking remedial measures such as noise barrier installation. However, it has been posited for some time that sustainable approaches to environmental noise control need to involve qualitative assessment methods too (e.g. [2, 3]), particularly as the widely used A-weighted acoustic parameters are now thought to be poor indicators of annoyance in cases where there is a high amount of energy in the low frequency range [4].

In architectural acoustics there are well-established subjective parameters that may be used to assess the sound quality in concert halls and auditoria (e.g. [5]). Furthermore, modern auralisation techniques allow the designers of all kinds of interior spaces to audition and evaluate the acoustics prior to their construction. By contrast, in the design and regeneration of urban outdoor spaces, little consideration tends to be given to their acoustics beyond the level-based noise impact assessments that are required if the development is to be in the vicinity of noise sensitive receptors such as dwellings and schools.

The aim of this research is to investigate the application of auralisation and soundscape methodologies in relation to environmental noise management. To this end, we present a case study in which we have used auralisation in conjunction with a novel listening test framework to assess the impact of a proposed noise treatment on the perceived sound quality in a real urban environment. The form of noise treatment chosen for the investigation is intended to reflect the more 'holistic' attitudes to environmental sound adopted in soundscape research - i.e. one which considers the social and aesthetic aspects as well as the physical. For this reason we have taken the example of the *sonic crystal noise barrier* - a device which has been investigated by both scientists and artists with a mutual interest in soundscape [6, 7, 8]. It is also compatible with the soundscape philosophy, in that a sonic crystal noise barrier may be designed for reasons other than reducing overall sound levels, such as altering the spectral qualities of a soundscape, and encouraging active engagement with it. However, the example is predominantly illustrative, with the main focus of the investigation being the novel application of auralisation and soundscape methodologies in an environmental noise impact assessment.

In order to assess the impact of a sonic crystal noise barrier on the perceived sound quality in a specific location, we have used auralisation techniques to assimilate a 'natural' listening experience - albeit in a virtual acoustic environment. To perform the evaluation, we have adopted qualitative test methodologies resembling the questionnaires and semantic scales adopted by Raimbault [9], and the *structured listening walk* - also referred to as a *sound walk* - initially proposed by Berglund and Nilsson [10]. The objectives behind the experiments are thus twofold: firstly we are interested in whether the proposed *virtual sound walk* methodology can elicit experiences similar to a real sound walk; and secondly, we ask whether it is appropriate for

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assessing the impact of potential noise treatments or other modifications to the soundscape. Each of these represents a novel contribution to the field which, it is hoped, will also bring about new insight into perception of environmental noise, and about alternative approaches to its management.

The paper is organised as follows. In Section 2 we describe the research context for this programme of work. Section 3 describes the experimental schema used to auralise the soundscape. The schema can be broken down into two main components: the first consists of an initial site survey; and the second concerns the auralisation processes leading to the rendering of the soundscape in a multi-dimensional loudspeaker array. Section 4 describes the subjective analysis of the soundscape auralisation in the virtual sound walk test framework. Finally, our main findings are summarised in Section 5.

2. Background

2.1. Environmental Noise

Environmental noise is generally considered to be *unwanted sound* in the environment, and is regarded in psychological terms as an environmental *stressor*. While its effects are not fully understood, it is known to cause annoyance which may lead to increased stress and its associated physical symptoms in some individuals. Furthermore, sudden loud noises and low level continuous noise are both known to cause sleep disturbance, which is in turn linked to a number of physiological and performance-related side-effects (e.g. [11, 12, 13]). However, relationships between environmental noise and its suspected health effects are quite complex, noise being just one amongst many environmental stressors encountered in day-to-day living. There is also the question of how one defines unwanted sound, given the subjective nature of auditory perception. While there may be a strong tendency for or against certain sounds based on physiological or social factors, reactions to sound are also inextricably linked to an individual's personal and cultural experiences, present mood and situation. In which case, *how does one distinguish between 'good' and 'bad' sound?*, and *is it ever appropriate to generalise regarding environmental acoustic preference for a given population?* It is considerations such as these which have been given a great deal of attention in recent years, particularly in the interdisciplinary field of *soundscape research*.

2.2. Soundscape Research

The term *soundscape* can be defined in a number of different ways. Here it refers to all the sounds that are heard in a particular location, considered as a whole. Soundscape research not only recognises but pays particular attention to the reciprocal relationship humans share with the environment. Being closely linked to acoustic ecology, it seeks for sustainable ways to manage environmental sound that benefit both humans and nature, as well as considering the social and economic needs of a population. In this respect, there is also an element of overlap with environmental psychology, where attention is given to building and testing theories in order to explain and predict human-environment interaction [14].

Soundscape research originated in the 1970s following publications by a group of composers based at the Simon Fraser University in Vancouver (e.g. [15, 16]). In 'Soundscape: The Tuning of the World', Schafer calls for a re-evaluation of the changing acoustic landscape. He asserts that, through our active engagement with the sounds around us, we can discriminate between sound and 'noise' and take better care of our acoustic environments. What emerged then as a philosophy, has since penetrated multiple disciplines, as those who share it have sought to integrate it with their work in areas such as acoustics, ecology, sociology and urban design (e.g [17, 18]).

Since the late 90s research momentum has intensified, with many scientific studies contributing to the collective understanding of soundscapes. These have included the development of new systems of documentation (e.g. [9, 19]), understanding and predicting subjective response (e.g. [20, 21]) and evaluating the acoustic impact of specific urban design features (e.g. [22, 23]). Within this broad and comprehensive array of research output, it has been widely acknowledged that soundscape analysis has an important part to play in environmental noise control, and that sustainable approaches should not rely entirely on level-based assessments, but also on new, qualitative assessment methodologies (e.g. [2, 3]). The next steps are therefore toward their incorporation in standard assessment procedures.

We are proposing here that a virtual sound walk could offer practitioners the option of incorporating qualitative evaluation into noise impact assessments and urban design processes. In the case of large developments, this could be included as part of a wider socio-acoustic survey. For smaller projects it could be used to assist the interpretation of quantitative data, or to help qualify the intended design strategies with meaningful subjective data.

3. Experimental Methods

3.1. Initial Site Survey

Before embarking on the design of the proposed barrier structure, several things need to be considered in relation to the space for which it is intended. First and foremost, a decision must be made regarding a suitable location for the case study. This should be a public area, preferably one with a vibrant soundscape, and one that is known to suffer from the adverse effects of environmental noise. In these respects, it is thought that Woodhouse Moor in Leeds would be an ideal location.

Woodhouse Moor, also known as Hyde Park, is an area of green space approximately one mile from Leeds city centre (Figure 1). The city of Leeds is situated within the West Yorkshire urban area and is estimated to be the third most populous city in the UK according to the 2011 census [24].

Woodhouse Moor is comprised of 3 parts: a formal park of around 26 hectares (260,000 m^2) on the west of Woodhouse Lane, and two other open areas to the east of it.

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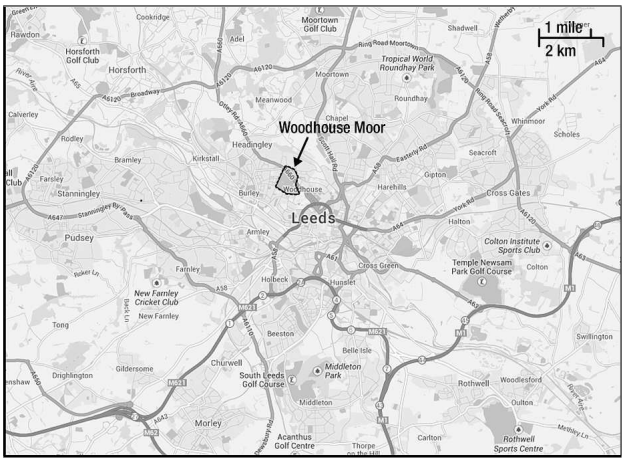


Figure 1. The West Yorkshire urban area showing Leeds and Woodhouse Moor. ©Google 2013.

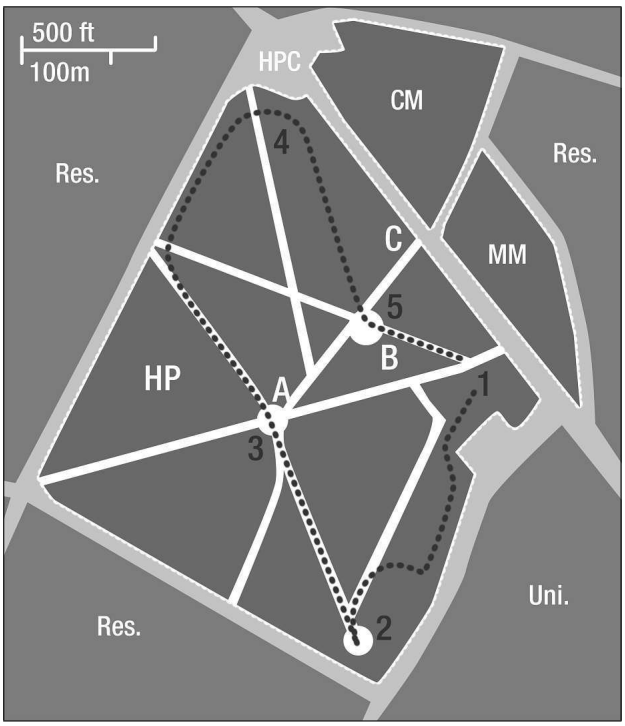


Figure 2. The Woodhouse Moor area. MM = Monument Moor, CM = Cinder Moor, HP = Hyde Park (main park area), HPC = Hyde Park Corner. Res. and Uni. indicate Residential and University areas respectively. The dotted line shows the route of the sound walk (see 3.1.2) with the numbers 1-5 indicating the five stopping points. The letters A, B and C indicate the approximate recording locations that were used in the auralisation (see 3.2).

These are known as the Monument (or Upper) and Cinder (or Gravel, or Lower) Moors which are used for events such as circuses and sporting matches, and sometimes car parking (Figure 2).

As of 2005 the park had just under 3 million visits a year and is the second most popular urban park in Leeds according to a report published by Leeds City Council in 2006 [25]. Being situated close to the city's Universities makes it a popular social venue for the city's large student population. The park is also host to a variety of public events, including Unity Day - an annual festival with live music and multicultural activities. The park has five main paths which meet in the centre, each of which is tree-lined, and together they divide the park into different areas of usage. For example, the North-Eastern corner of the park houses the children's play area, skate-park, picnic area, basketball courts and public conveniences; to the West are the allotments and tennis courts; and to the East are gardens and dedicated nature areas.

The Woodhouse Moor area is known to be adversely affected by environmental noise, its two primary sources being road traffic (the park is bordered by roads, one of which is dual carriage-way and a main artery to Leeds city centre); and aircraft flying to and from Leeds-Bradford Airport. The area was considered for the case study following its recommendation by a member of Leeds City Council's Environment Protection Team.

The next step is to determine how the space is currently being used; to identify any specific noise concerns - particularly those that breach noise guidelines detailed in the European Noise Directive (END) [1]); and to gain a general impression of the soundscape, highlighting both its strengths and its weaknesses. At that point it will be possible to outline the purpose of the noise intervention in precise terms and consider its desired effect. In an effort to get there, we have determined to carry out two types of acoustic survey: a quantitative survey, involving detailed noise mapping of the affected area; and a qualitative survey, in the form of a sound walk accompanied by a questionnaire.

3.1.1. Noise Mapping

A noise map is a graphic representation of the sound pressure level (SPL) spatial distribution in a region, and is usually represented using contour lines - much the same as a topological map. Nowadays it is unusual to obtain the SPL data through direct measurement; a more common technique involves using computational tools based on noise models to generate the maps. The latter technique is generally favoured on account of its high accuracy, lower cost and because it offers the ability to control certain parameters (times of day, atmospheric conditions etc.) in order to produce a large number of yearly averaged readings.

In this case, long-term averages are not desirable, since we are specifically interested in the soundscape during the park's busier periods (i.e. daylight hours, fair weather). This is because the noise map is intended to represent the SPL distribution of the park at times when more people are using it. These are also representative of the conditions experienced when making recordings and conducting sound walks.

While there are no strict guidelines for noise mapping, we tried, where possible, to observe recommendations in [26] and [27]. The general noise mapping procedure involves dividing the space under observation into a grid of receivers and carrying out a minimum of 2 x 2 minute $L_{Aeq,T}$ measurements at each coordinate on the grid. $L_{Aeq,T}$ is a standard measurement parameter used in noise assessment and refers to the A-weighted, equivalent continuous

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sound pressure level averaged over the period of observation, T. It is then possible, using Fourier analysis, to obtain separate $L_{Aeq,T}$ readings for octave or 1/3 octave bands. In this case, measurements were recorded at octave bands ranging from 31.5 Hz - 8 kHz.

It is noted that, in most situations requiring a noise map, the $L_{Aeq,T}$ would be derived from more or longer measurements than the 2 minute measurements used here. Here, we are not motivated by the need for long-term averages, but a snapshot of the ambient sound levels representative of a normal day in the park. However, due to the relative shortness of the measurements, the resulting noise maps cannot be relied upon for the estimation of long-term noise exposure, or the derivation of community noise indicators such as L_{dn} and L_{den} which, in accordance with ISO 1996-2:1987 [26], should be based on 1-hour L_{eq} measurements.

The coarseness of the grid generally depends on the size of the area being mapped, and can range from just a few to several hundreds of metres. In an area as small as Hyde Park, a noise mapping tool might set the distance between receivers at 10 m, but this would have made for an impracticably large number of measurement positions. A rectilinear grid with a resolution of 50 m was therefore chosen, and a least squares method of interpolation was subsequently used to refine it by a factor of 5. Measurements were made approximately 1.5 m above tread level, as recommended in [26]. After interpolation, the isolines of the map were plotted in Matlab in 5 dB ranges. Figure 3 shows the resulting noise maps in the 31.5 Hz and 1 kHz ocatave bands. We find the 31.5 Hz band to be of particular interest as it is the only region to exhibit SPLs that could be problematic if sustained over a long period (considered in terms of the guideline amounts). By contrast, A-weighted SPLs in the more perceptually sensitive 1 kHz region appear significantly lower.

As expected, noise was distinctly more dominant in the lower frequency regions, particularly in the 31.5 and 63 Hz regions. There are a few isolated areas in which the sound pressure levels would exceed limits recommended by the WHO [28] - one being around the skate-park, and another close to the junction in Hyde Park Corner (labelled as HPC in Figure 2), noted as being closest to points (4) and (5) in Figures 2 and 3. Although maximum levels are noted as being 83 dB(A) L_{eq} in the lowest octave band, this may well have been due in part to adverse weather conditions on the day of recording. However, the higher levels noted here are certainly indicative, and it is the distribution of noise levels in Figure 3 that is the most important aspect to note. Note further that sound levels are generally below 65 dB(A), as shown in the 1 kHz plot, and thus within the recommended daytime limits.

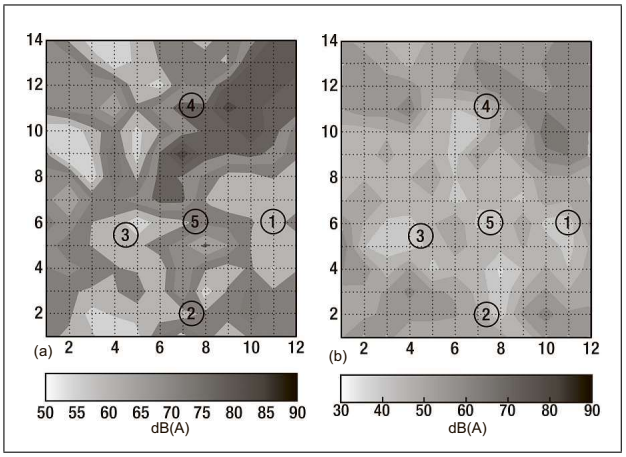


Figure 3. Noise maps showing the A-weighted SPL distribution in the (a) 31.5 Hz and (b) 1 kHz octave bands. Highest levels are noted around points (4) and (5) with a maximum measurement of 83 dB(A) noted, due in part to adverse weather conditions at the time of measurement. The distribution of levels is the key point to note however, with the areas with most significant levels corresponding to key site features, such as a busy road junction, or the skate-park. The complete set of noise maps are given in [41].

3.1.2. Sound Walk

Methods of soundscape analysis vary significantly depending on the purpose of the research and the discretion of the researcher. The sound walk methodology adopted here is largely based on Berglund's and Nilsson's *structured listening walk* which they proposed as a tool for measuring the perceived soundscape quality in urban residential areas [10]. A sound walk essentially involves leading a group of participants along a predefined route throughout which the aim is to concentrate on what can be heard and the physical environment. It was felt in this case that the 90 minute duration of Berglund's structured listening walks would be inappropriate given the relatively small area being studied. It was therefore decided that an approximate duration of 60 minutes would be adequate for our sound walk, allowing 30 minutes walking time, 10 minutes for the introductory talk and warm-up, and 20 minutes for shared reflection. At 5 pre-identified locations shown in Figure 2, participants were asked to stop and listen in silence for a short period of time before answering some location specific questions. In the first of the questions they were asked to rate the affective quality of the soundscape on a semantic differential scale. The semantic differential scale used here is one originally proposed by Raimbault [9] consisting of 9 pairs of adjectives, 7 of which assess auditory attributes of the soundscape, and 2 of which relate to the emotional impressions of the listener. The semantic pairs are listed in Table I and were assessed by the listeners using a 7-point Likert type scale. While listeners were not given explicit training on their use, they were encouraged to ask for clarification on any terms they were unsure about. Short explanations like the ones given in Table I would then be offered by the test administrator. Concerning the choice of attributes, there was the wish to utilise prior research rather than introducing a new set of terms which would warrant a separate investigation. Raimbault's metrics were chosen here because they promote a 'holistic' approach to soundscape auditory processing, which is more appropriate to qualitative assessment than the converse, 'descriptive' approach wherein the subject focuses

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Table I. Semantic differentials for assessing the affective quality of a soundscape. * indicates emotional attributes.

Attributes	Explanation
Quiet/Loud	How loud or powerful is the sound?
Weak/Strong	Is the sound subtle/vague, or does it tend to 'take over'/seem very pronounced?
Harmonious/ Disharmonious	Do the sounds seem to blend well with each other and the surroundings, or are they incongruous?
Unique/Common	Does the soundscape seem unusual, or is it quite typical?
Warm/Cold	Related to timbre and the overall frequency balance (i.e. does the sound seem balanced/unbalanced?)
Varied/Monotonous	Is there much change occurring over time?
Soft/Rough	Relates to the temporal change/fluctuation (i.e. is it steady, or unsteady?)
Pleasant/Unpleasant	Do you like it?
Comfort/Discomfort	Does it make you feel relaxed or stressed?

on individual sources. This observation is also echoed by Castellengo and Dubois [30] who differentiate between the 'identification' and 'qualification' modes of soundscape processing.

A total of 16 participants aged between 21 and 56 took part in the sound walk, of which 5 were female, and 6 were non-UK nationals. This was deemed appropriate given the mix of nationalities and ethnicities among the local student and residential populations. The gender bias was not deliberate, but unavoidable due to the method by which participants were recruited. Recruitment was through adverts in local cafés, and, due to the limited number of respondents, there was no opportunity to be selective.

In addition to using the semantic scales, participants were encouraged to record their comments and observations in their own words, both in relation to each stopping point and more generally. Prior to commencing the sound walk, they were also asked to answer several questions concerning their professional background, usage of the space, and their expectations/preconceptions about the sound of urban spaces.

3.1.3. Results of Sound Walk

From Figure 4, the results of the semantic differential scaling seem to indicate there may be significant differences between locations 3 and 4 compared with locations 1, 2 and 5. To test this theory, statistical hypothesis tests were performed after first subjecting the data to a suitable form of normality test. When dealing with relatively small data sets, the Shapiro-Wilks [31] test is often used to check for normal distribution. Using this method, it was found that the majority of the data is not normally distributed when

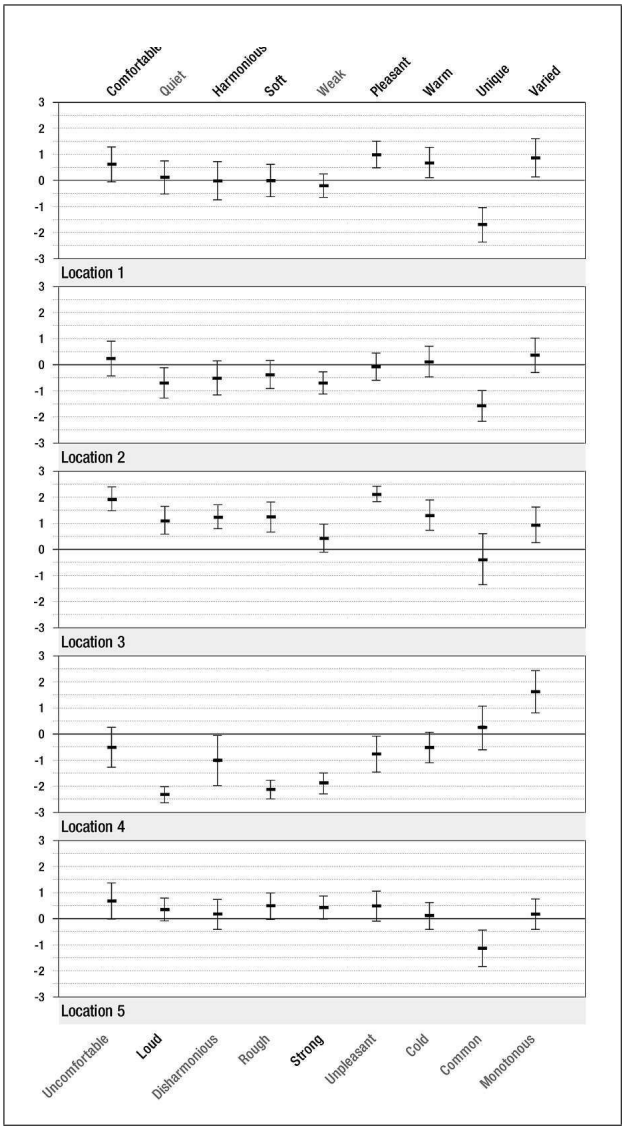


Figure 4. Rated sound quality in 5 areas of Woodhouse Moor using soundscape quality metrics. Sample size: 16.

tested with a 5% significance level. There are several explanations for this. Looking at the histograms (see Figure 5), it is apparent that, in some cases, there is an obvious skewness in the data which is thought to have resulted from responses tending toward the extreme ends of the differential scale. It is also apparent that in some other cases the distribution may be bimodal, indicating that the population under test is split between two different extremes. This may be a genuine division due to the relative nature of the descriptors - for example, one would expect that participants who spend more time in the country might have different acoustic perceptions from those who spend more of their time in big cities - or it may be due to how the individuals have interpreted some of the descriptors. While a separate investigation on the use of Raimbault's descriptors might offer further insight, it was beyond the scope of this study.

Due to the distribution of the data, it was necessary to use a non-parametric form of hypothesis test to determine whether the apparent differences between locations

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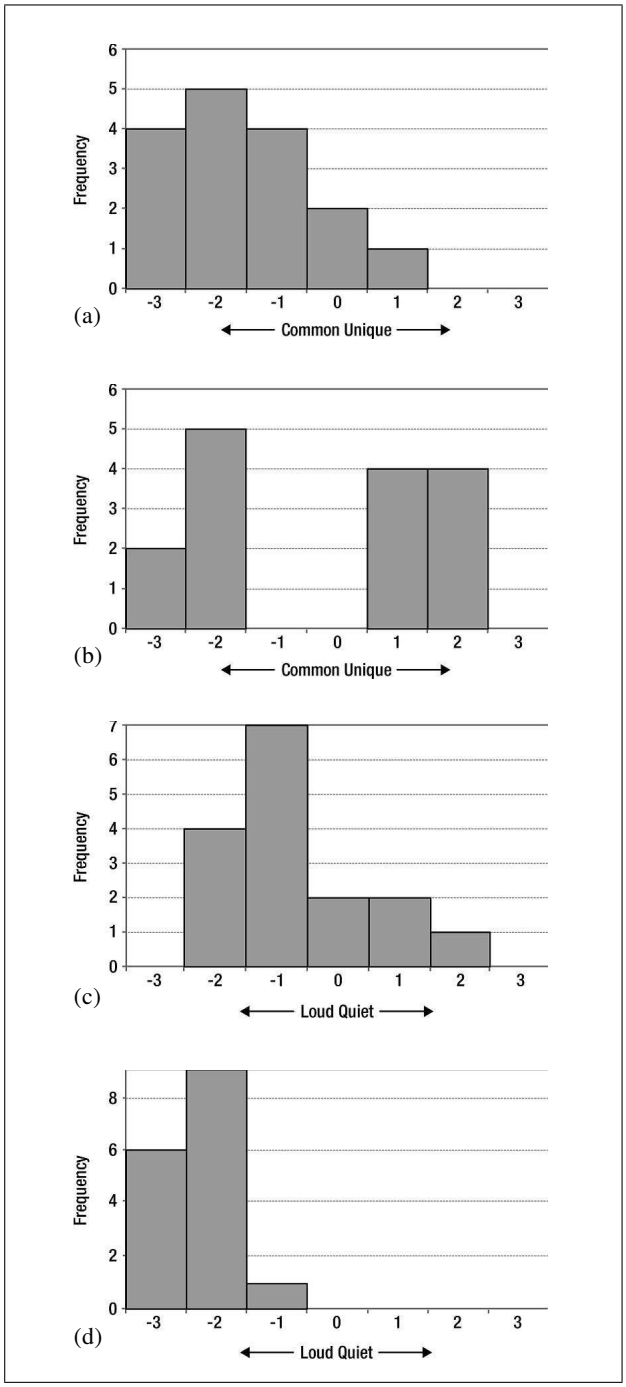


Figure 5. Some examples of histograms showing distribution of responses to semantic differential scales. (a) Location 2 - Common/Unique, (b) Location 3 - Common/Unique, (c) Location 2 - Quiet/Loud, (d) Location 4 - Quiet/Loud. The complete set is published in [41].

are statistically significant, or likely to have occurred by chance. Since the soundscapes in locations 1, 2 and 5 appear similar, it was decided that only one of these locations, location 2, would be contrasted with locations 3 and location 4 independently. The type of test chosen was the Mann-Whitney U-test [32], a well known non-parametric statistical hypothesis test suitable for small and arbitrary sample sizes. However, the U-test does assume that the

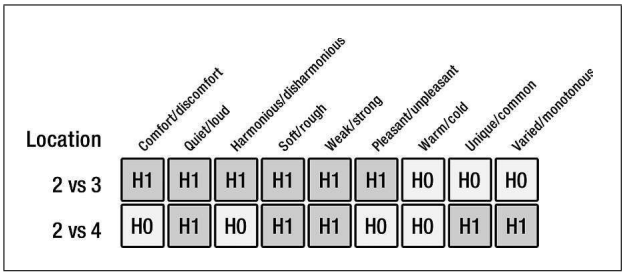


Figure 6. Results of significance test between data sets in different locations. H0 indicates null hypothesis not rejected (ie. no significant difference), H1 indicates null hypothesis rejected with 99% confidence (ie. difference is significant).

distributions of the data sets under comparison are similar, which may make some of the results less reliable than others. The results of the U-tests are interpreted as follows: if the null hypothesis is rejected, one data set tends to have significantly higher or lower values. If the null hypothesis cannot be rejected, it is assumed that the data sets are not significantly different. The results have been calculated with a probability of error value of $\alpha = 0.01$ and are given in Figure 6. H_0 indicates the null hypothesis has not been rejected, while H_1 is an indicator that the null hypothesis can be rejected with a 1% probability of error, which is equivalent to a 99% confidence level.

3.1.4. Discussion

The results of the semantic differential scaling test show there is a high level of variation in subjective response. While this may partly be due to the descriptors that were used, the extent of the variation also highlights the inherent difficulty in predicting reactions to environmental sound. Nevertheless, there was statistical significance in some of the responses to locations 3 and 4 which had also provoked the strongest reactions in subjects' comments and the group discussion. For example, there was a very positive response to location 3, which was widely considered the more pleasant, comfortable and harmonious of all the locations. Interestingly, despite scoring highly on loudness, roughness and strength, the area with the highest recorded SPLs, location 4, was not considered significantly unpleasant or uncomfortable. Verbal remarks on this soundscape were generally positive and included adjectives such as 'rich' and 'vibrant', although participants also stated it was not somewhere they would come to relax.

On the basis of these results it would seem that variation and contrast are important components of a soundscape and areas with high sound levels are perceived positively. Expectation is also a critical element, as listeners tend to be more annoyed by unexpected or incongruous sounds - i.e. sounds which seem 'out of place' - whereas the same sounds in a different setting might be perceived quite differently. Another issue that was raised was the effect that the participants' own involvement had on their perception. Almost all participants recorded that the experience had increased their appreciation of the soundscape as a result of taking the time to actively listen to the sounds around them. They also noted their surprise at the vari-

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ety of sounds heard. This reinforces the idea that better management of environmental noise should include aiding and encouraging public engagement with soundscape. To give some examples, this could come from public art installations, informative displays, soundscape events, and creative forms of noise intervention such as sonic crystal structures - all of which could benefit from auralisation.

3.2. Auralisation

Methods of auralisation vary quite considerably and processes are therefore devised with respect to the intended application. In this work, the auralisation is primarily for the purpose of evaluating subjects' response to a noise intervention, of which the example we are considering is a sonic crystal noise barrier. With this in mind, the emphasis is on reproducing a real soundscape convincingly and consistently, wherein the physical effects of the intervention on the sound reaching the listener are perceived as accurately as possible. The approach is therefore to take genuine, spatially encoded, B-format recordings of the soundscape and try to approximate the presence of a sonic crystal noise barrier using acoustic modelling techniques. As mentioned previously, the reason why a sonic crystal noise barrier has been chosen for this example is on account of its diverse appeal, being something which is of interest both as a practical device, and as an object of art. This we feel makes it an ideal candidate for auralisation.

The process of rendering the final auralisations is summarised here as follows:

1. Obtain the transfer function of the sonic crystal structure in 3-D finite different time domain (FDTD) simulations. The transfer function shall be obtained in the form of an Impulse Response (IR).
2. Design filters to separate the sound incident on the barrier into two portions: diffracted and incident sound. These equate to the sound that a listener receives due to diffraction over a thin rigid screen; and that which would be reflected from the screen's surface.
3. Apply the reflected sound filter derived in Step 2 to recordings made in position C, close to the primary noise source.
4. Convolution of the result from Step 3 with the sonic crystal IR recorded in Step 1.
5. Apply the diffracted sound filter derived in Step 2 to recordings made in position C.
6. Summation of the result from Steps 3 and 5 with the diffracted portion of the signal in the time domain.
7. Summation of the result from Step 6 with ambient sound recorded in position A.

The recording positions A, B and C have been depicted in Figure 2. Location B is the approximate location of a listener situated in the proximity of the proposed barrier location, while locations C and A are used to obtain recordings wherein the primary noise source is, respectively, more or less dominant.

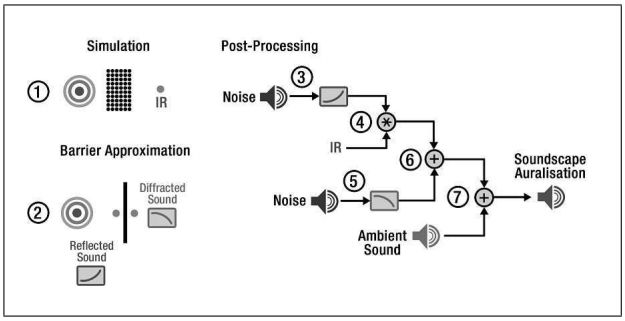


Figure 7. The step-by-step process of auralising a sonic crystal barrier. In Step 2. Maekawa's formula is used to derive the filter coefficients needed to obtain the diffracted and reflected portions of the signal.

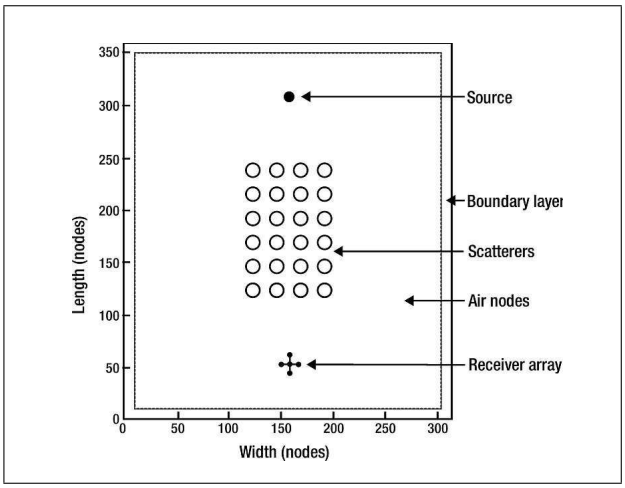


Figure 8. The simulation set-up for recording the impulse response of a 4-by-6 cylindrical sonic crystal array in the square lattice configuration.

3.2.1. Barrier Modelling

The FDTD method was used to model the propagation of acoustic waves through the sonic crystal barrier. The method has proved highly effective in a variety of problems intended for auralisation, largely on account of its speed, efficiency and the relative simplicity of the computer algorithms by comparison with other wave-based methods such as the Finite Element Method (FEM). Furthermore, it is more suitable for problems concerned with wave interference effects than geometrical acoustic methods.

A variant of the FDTD method that is applicable to linear acoustic systems has been thoroughly documented by Schneider [33]. Here it has been used to model a 2-D sonic crystal array in a 3-D rectilinear mesh with PML absorbing boundary condition applied [34, 35]. In this case the array was 4 columns wide and 6 rows deep with elements arranged in a square lattice configuration (Figure 8). The radii of the cylinders was 35mm, corresponding to a filling fraction of 0.32, which is within the optimum range for the elicitation of a complete band gap according to some sources (e.g. [36]). An estimate of the transfer function was obtained by exciting the mesh with a driving func-

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tion at a single source node, and recording the impulse response (IR) at a receiver node on the opposite side of the array. To enable a comparison, an IR was also obtained using the same source-receiver configuration but with the array absent. The frequency responses of both IRs is given in Figure 9.

In preparation for convolving the noise source with the sonic crystal IR, the proportion of sound incident on the barrier surface is estimated relative to the proportion that would be diffracted over the barrier top. For this, the authors have referred to the standardised procedure for estimation of the frequency dependent attenuation afforded by a thin rigid barrier, ISO 9613-2:1996 [37]. The standard prescribes a formula for this purpose which is based on a curve derived from empirical measurements performed by Maekawa [38]. The formula assumes the barrier has finite height and infinite length, and that it is a perfect reflector. By these assumptions, it allows an approximation of single-edge diffraction by the barrier. This method is used here, applied as shown in Figure 10, to generate a frequency weighted amplitude envelope, as presented in Figure 11, which, when applied to a recording of the source sound, yields an approximation of the diffracted sound. The inverse of the filter is then used to estimate the 'incident' portion of the sound - i.e. that which was absorbed or reflected away from the barrier surface. It is this incident portion which will be convolved with the sonic crystal IR.

3.2.2. Rendering the Soundscape

Ambisonic B-format sound recordings were made using a Soundfield ST450 microphone and a portable digital audio 4-track recorder. Three recording locations were used - one close to the primary source of noise (i.e. the road), one at the proposed site of the barrier (location 5), and a third in location 3 where the primary source was less dominant. The reason for the different locations was to create a degree of artificial separation between sound reaching the receiver from the direction of the source (via the barrier), and sound reaching it from other directions, as it is only the former we are seeking to transform. The microphone gain is kept at a consistent level in all of the recordings.

From the recordings, we produce the virtual soundscape by combining noise-dominant sound files (to be filtered with barrier IR), and noise-subdued sound files (unfiltered) - the latter representing sound arriving from other directions. The coincident nature of the B-format microphone array implies that phase differences imparted due to the array itself when mixing multiple signals are minimised. Furthermore, owing to the complexity and non-correlated broadband nature of the background ambiences captured in the recordings, it is possible to cross-fade between different segments of audio without any discernible inconsistencies. In terms of the potential for localisation discontinuities, it is also helpful that most of the ambient sounds are not perceived to originate from a fixed point - i.e. they consist of many moving sources which are subject to varying meteorological conditions - hence any inconsistencies are not noticeably increased as a result of superimposing sound files. However, care must be taken when handling unique sound events not to break the illusion of a single, continuous recording and stable soundscape.

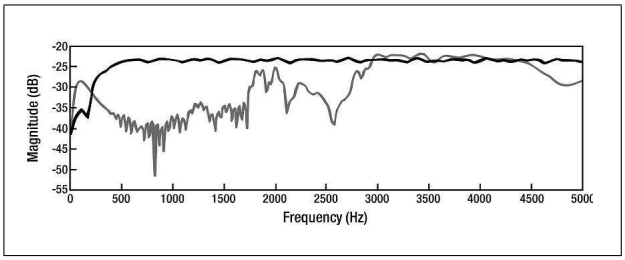


Figure 9. Frequency response curves of IRs recorded in 3-D FDTD simulations of a point source before (black) and after (grey) insertion of a 4-by-6 sonic crystal array.

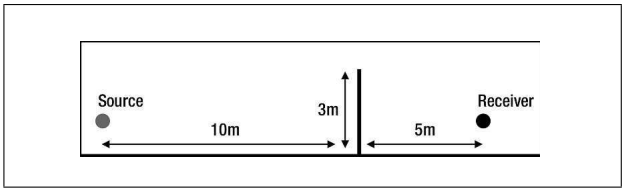


Figure 10. The source-barrier-receiver scheme of the virtual barrier. Inserted into Maekawa's formula, the values used in this example produce the envelope pictured in Figure 11. Note that the values are essentially arbitrary and can be adapted for different configurations.

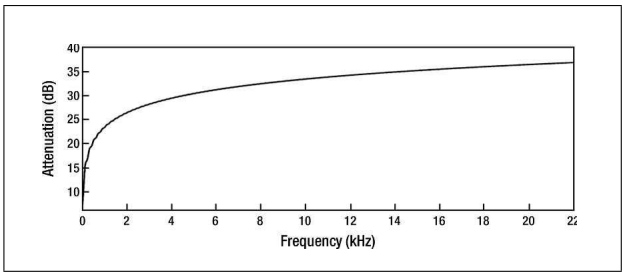


Figure 11. Frequency response of the amplitude envelope corresponding to the thin rigid barrier pictured in Figure 10.

The arrangement of the soundscape from the recordings takes place in a Digital Audio Workstation (DAW). Prior to this, the recordings were auditioned and annotated according to their content. This included making records of all the unique and intermittent sound events that were captured, as well as any noticeable variation in the continuous background ambience, which were considered to be the flow of traffic on Woodhouse Lane, birdsong and wind in the trees. Individually distinct vehicle pass-bys were classed as unique sounds. An arrangement was then built up of these elements which would give a realistic reflection of the soundscape in the proposed site at both quiet and busy periods. It is noted that, while the recordings were not made during the real sound walks, the conditions in which they were made were similar (e.g. mid-week, daytime, fair weather), hence it is reasonable to expect they are representative of the soundscape experienced by listeners on the sound walk. This assumption will either be confirmed or disputed when the virtual soundscape is evaluated and the results compared with those of the real sound walk.

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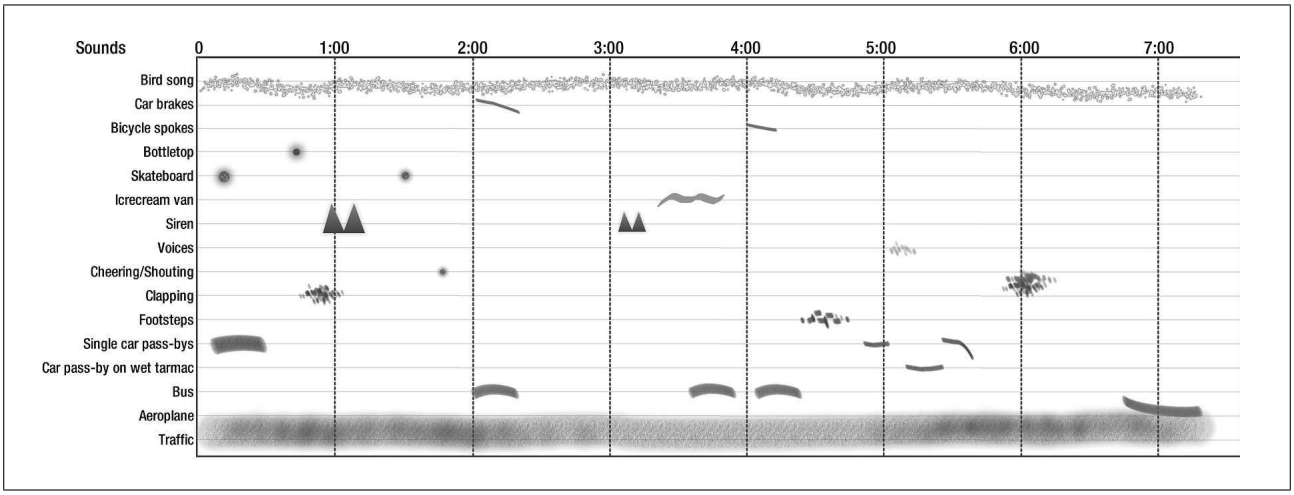


Figure 12. A graphical score illustrating the overall structure of the soundscape composition.

One of the issues faced when producing the arrangement was how to convey the diversity of the soundscape within a relatively short time frame. Whereas participants in the real sound walks spent over an hour in the environment and therefore had much more opportunity to observe its multiplicity, participants in the virtual sound walk will have only a few minutes in which to form their impressions. Restricting the length of the virtual sound walk to a few minutes was deemed necessary, both for logistical reasons related to the test methodology, and to prevent the onset of fatigue amongst participants. Essentially one needs to compress the soundscape in time, yet without compromising its authenticity. The arrangement therefore tries to create a balanced impression by including busier periods when a lot of sound events are taking place, either side of a less active period in the middle. It is hoped that by structuring the composition in this way, it not only creates a balanced impression, but also conveys a sense of movement, reminiscent of the transitions that occur in a real soundscape during its daily life cycle. Figure 12 is a graphical representation of the composition in which identifiable sound events have been plotted against time. As well as giving an approximate indication of the onset/offset of unique sound events, the vertical positioning and graphical style of each event is intended to convey a rough sense of its pitch and timbre.

Having prepared the arrangement, separate mixes of the source-dominant tracks and source-subdued tracks are exported from the DAW so that the barrier estimation and convolution processes can be performed in Matlab. The source-dominant mix is filtered with the barrier frequency weighted amplitude envelope, before being convolved with the sonic crystal IR, and recombined with the source-subdued sound (representing sound arriving from other directions).

4. Virtual Sound Walk

In this second group of listening tests, a condensed version of the original sound walk questionnaire was used, in which the psychometric tests were retained, along with the space for free comments. As in the original sound walk questionnaire, participants are explicitly asked to list all sources of sound they pick out, including individual words or phrases. Since there is no actual 'walking' involved, the questionnaire need only concern the location of interest - hence the duration of the test is much shorter, comprising of around 7 minutes of listening material and a further 10 minutes or so for answering questions. A total of 27 participants were used in the virtual sound walk, of which 12 formed the control group, and 15 formed the sonic crystal group. All were aged between 21 and 64, and between the two groups there were 12 non-UK nationals and 9 females.

The listening material was presented over a mixed order ambisonic array, whereby the higher order signals were extrapolated from the 1st order signals by the Harpex [39] ambisonic decoder plug-in for Reaper [40]. The array consisted of a total of 16 loudspeakers distributed in a 4-by-8-by-4 circular configuration (see Figure 13). Using a higher order ambisonic set up extends the sweet spot, thus optimising the set-up for several listeners or making the resulting sound field image more stable under head movement for a single listener. Note that the virtual sound walk was conducted for each subject individually. The virtual sound walk data consists of two sets: A control group of respondents (A) who were played the material processed with an empty mesh impulse response (i.e. no barrier present), and a second group (B) who were played the material based on the simulation of the 2-D sonic crystal barrier.

Some of the questions presented to participants in the virtual soundscape questionnaire were different from those that were presented in the original sound walk questionnaire. This is partially related to the fact that information pertaining to the nature and whereabouts of the soundscape location had been purposefully excluded from the participants. The reason for making the soundscape anonymous in these tests was to try to gain some insight into how expectation and learned association affects the way people value the sound around them. As before, the questions were divided over two sections: a section of pre-sound

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walk questions, and a section to be answered during and/or after presentation of the material.

In the pre-sound walk questions, participants were asked to provide some general information about themselves, such as their age group, nationality, sex and profession. They were also asked whether they had any involvement with acoustics or urban planning in their profession, and if so to give details. They were then asked about their general impressions of urban soundscapes in the UK, and their current attitudes towards environmental sound. The second half of the questionnaire included the differential scales used in the real sound walks, as well as several fairly broadly worded questions designed to encourage spontaneous observations, without being too suggestive. To ease them into the process, the first of these questions asked the participant to list all the sounds they were able to hear, and where they were unable to identify the source of the sound, to attempt to describe it in their own terms. The intention behind this question was to allow some speculation as to whether there was any change in clarity or definition due to the sonic crystal. For example, if participants tended to observe more different sounds with the sonic crystal present, it might suggest the masking effect of the traffic noise had been reduced. The remaining questions focussed on the participants' impressions of the soundscape, how they imagined it might look, what they might do there, and finally their feelings about the virtual soundscape experience, including any technical observations.

4.1. Results of Virtual Sound Walk

Here we are comparing the results of the semantic differential test from the real sound walk against those of the virtual sound walk *without* the presence of the sonic crystal in order to analyse them for significant differences. Whether or not the null hypothesis for significant difference is rejected should be the same for both forms of test if one is to conclude with reasonable confidence that the auditory experience in a virtual soundscape is close to that of the real soundscape it is modelled on. For this we have used the Mann-Whitney U-test [32]. In Figure 14, the results of U-tests between different real locations (real versus real) and real with virtual (real versus virtual) are presented for comparison. The null hypothesis (H0) indicates no significant difference between data sets for a given pair of descriptors. It is apparent from these results that, based on the differential scaling, there is virtually no significant difference in the perceived sound quality of the virtual soundscape and location 2. This is apparent whether they are compared directly (top row), or in the way they compare to other locations (bottom and middle rows). This could be interpreted in a number of ways. It could mean that the differential scaling method and choice of descriptors were unsuitable. However, were this the case, one would expect to see the null hypothesis across all results, as if selections had been made at random. Yet, from the results of the real sound walk in which different locations were assessed, we know that it is possible to identify differences in sound



Figure 13. The virtual sound walk listening test set-up.

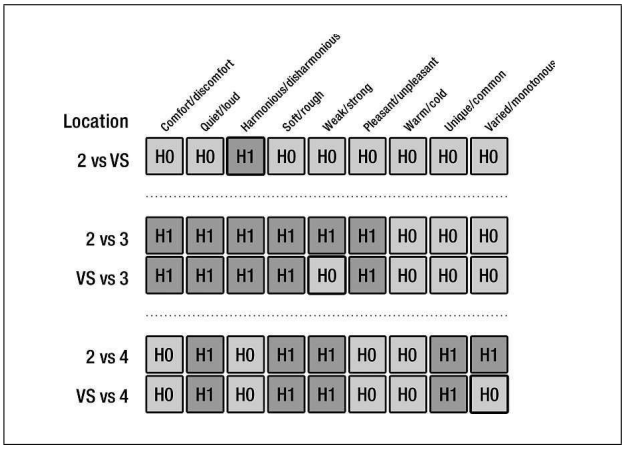


Figure 14. Comparison of the results from the significance tests between real versus real locations, and real locations versus the virtual sound walk (VS).

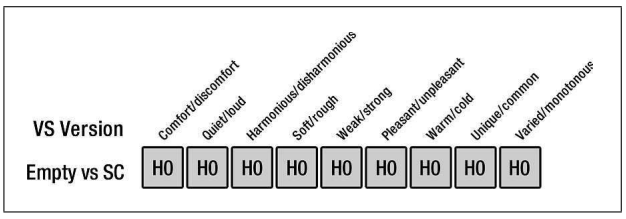


Figure 15. Significant difference tests between data sets recorded in the virtual soundscape experiments before and after inclusion of the sonic crystal barrier.

quality between different environments using this method. One would also expect there to be normal distribution in the data, which, as we have also seen earlier, was often not the case. Hence our preferred interpretation is that there was indeed similarity between the virtual sound walk and location 2, a claim which the verbal and written comments, and sounds identified support. We are therefore satisfied to take our experiment further, and compare the virtual sound walk before and after insertion of the sonic crystal.

In the next phase of the analysis, U-tests were performed between the virtual soundscape data obtained before and after auralisation of the sonic crystal (see Figure 15). The results of these tests appear to indicate that

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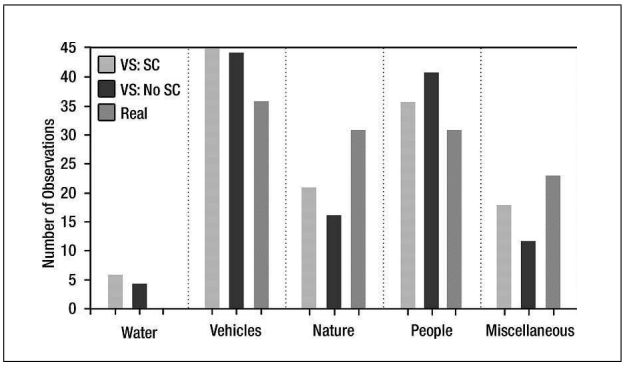


Figure 16. Sounds identified in real sound walk and in virtual sound walks before and after inclusion of the sonic crystal barrier. Due to differences in sample size between data sets, data has been normalised to a sample size of 15.

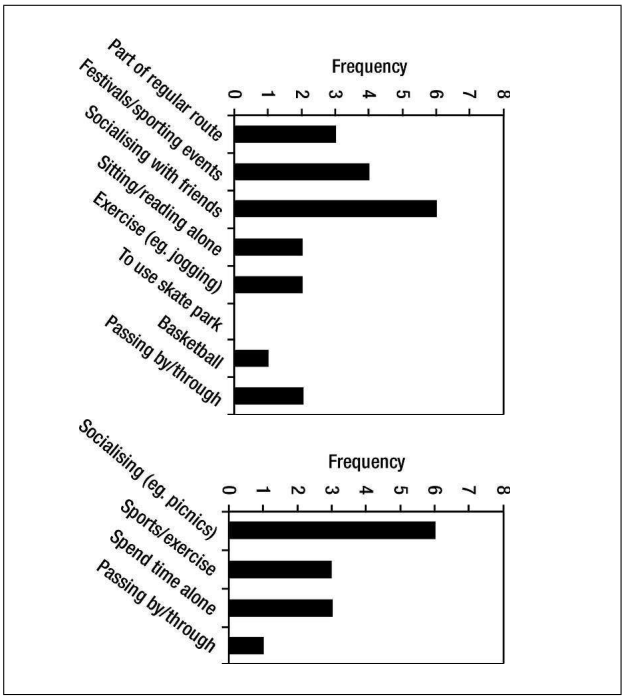


Figure 17. Activities that participants in the real sound walk associated with Woodhouse Moor (a) and those of participants in the virtual sound walk (b).

there are no significant differences in the perceived sound quality in either environment, when evaluated under 'normal' listening conditions. This is an interesting result, for while it has been demonstrated that subjects observed differences between short, stereo extracts of the composition heard in close succession [41]; here we have found that those differences do not constitute a significant change in the overall quality of the sound environment. We see this as evidence in support the case for advanced auralisation and new listening test frameworks in qualitative soundscape analysis

Figure 16 shows the frequency of different sounds perceived by the participants in both the real and virtual sound walks. Here, to aid graphical representation, we have grouped the observations into 5 main sound types, although the number of unique sounds identified by each participant was generally a lot more than 5. In both of the virtual sound walks the number of unique sounds identified by each participant averaged around 8, suggesting the sonic crystal neither heightened nor reduced the masking effect of the traffic sound. However, there was a difference in the range of sounds identified by each group collectively. For example, the control group jointly identified a total of 18 unique sounds, whereas the sonic crystal group jointly identified a total of 26 different sounds - an increase of approximately 80% after correcting for the difference in the group sizes. This might suggest that, while the listeners in the sonic crystal group could hear the same variety of sounds as the control group, they were less certain about the causes of the sounds - in other words, there may have been a rise in perceptual ambiguity as a result of the sonic crystal.

It is also noted that observations of natural sounds were fewer in the virtual sound walks than in the real sound walk, while observations of people and vehicle noises were more frequent. This may just be due to elements in the composition, but it could be interesting to consider in future work whether the artificial nature of the listening environment and/or absence of visual stimuli has an effect on listeners' sensitivity to natural/man-made sounds.

Attitudes regarding the activities subjects imagined they might partake in while visiting Woodhouse Moor were somewhat varied, yet showed some correspondence with those recorded by participants on the real sound walk. Figure 17 shows the activities participants on the real soundwalk associated with visits to Woodhouse Moor, compared with those that participants on the virtual sound walk pictured themselves partaking in. In both instances it appears the area was most favoured as a place for socialising, and was less popular for relaxation. Bearing in mind that, in the majority of cases, participants in the virtual sound walk experiments were not aware of the location, the similarity between these sets of data is taken as further evidence that the virtual soundscape successfully captured the ambience of the space.

4.2. Discussion

An assumption was made earlier that, while the recordings and sound walks were not undertaken simultaneously, the virtual soundscape was, nevertheless, representative of the real soundscape - qualitatively speaking. The results of the virtual sound walk experiment appear to support this assumption, showing that, in this particular case, listeners do have a qualitatively similar auditory experience in a spatial reproduction of a soundscape as they would in a real one. What is more, this is despite the absence of visual cues or preconceptions about the space. However, whether or not the same can be expected of other soundscapes requires further investigation, as it could be that the generic nature of this particular soundscape was partially responsible for the success of the reproduction, most participants having experienced similar environments in the past.

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While the variety of sounds identified by participants did not differ significantly between the real and virtual sound walks, the relatively short duration of the virtual sound walk suggests the statistical distribution of individual sounds may have. Further consideration for the potential uncertainty introduced by condensing events into a shorter time-frame might therefore be advisable.

Also interesting was that a number of participants mentioned hearing water, or initially mistaking the traffic for water. This also resonated with the real sound walk, as a few participants had then commented that from a distance they could imagine the road traffic to be water. It supports the notion that disassociation - whether due to acousmatic listening or a conscious effort - might lead to an enhanced qualitative experience. If this is the case, then while the sonic crystal barrier may not have had a significant effect on the sound that was heard, its visual impact may well have done. This theory is supported by a number of past studies into the effect of visual stimuli on auditory experience (e.g. [42, 43, 44]).

5. Conclusions

In this study we attempted to subjectively evaluate an urban sound environment before and after the insertion of a sonic crystal noise barrier using a combination of auralisation and qualitative test methodologies developed in the field of soundscape studies. We have also compared the results of the evaluation without the sonic crystal against results collated in the real environment.

In our analysis of the results we found there to be a significant similarity in the data obtained from the real and virtual sound walks. From this we have concluded the virtual sound walk method is a viable way to assess the impact of noise treatments on perceived sound quality before their construction.

In the series of paired comparison tests performed in [41] in which the same modelling methodologies were used, significant differences were perceived between audio material in which a sonic crystal was simulated, and that which was left untreated. However, the virtual sound walk experiments performed here have indicated that, in spite of these differences, there was no significant impact on the perceived sound quality in the environment due to the introduction of the noise barrier. This suggests that either dramatic changes are needed to effect a change, or that there are other factors at play that were obfuscated in the auralisation set-up. For example, the experiments support the notion that expectation and visual ambience have a marked effect on auditory perception - often more so than the sonic details. This leads us to suppose that altering the visual aesthetics of an urban space may, in some cases, do more to alter the perceived sound quality than attempting to augment the soundscape in the physical sense.

It also seems to be the case that strengthening the human-environment relationship through active engagement and attention to one's environment could have a much more marked effect on sound quality than subtle changes in its acoustics. While many studies have shown there is a tendency toward natural sounds, it is our belief that the idea of natural sound as 'good' and 'man-made' sound as bad is not particularly helpful, as it does not serve to promote positive, or ameliorate negative associations. Urban environments are acoustically rich environments, hence it is not always helpful to speak generally about a given soundscape in positive or negative terms as they can arouse both responses at different times and among different subjects. In future work the authors would therefore consider the circumstances surrounding positive and negative experiences of the soundscape, exploring aspects such as the attention of the listener, influence of visual and other sensory stimuli, and the attitudes and mood of the individual - aspects which may be illuminated through auralisation.

Acknowledgement

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