SUBJECTIVE EVALUATION OF URBAN SOUNDSCAPE AURALISATION BASED ON COMBINED RAY-TRACING AND RADIOSITY (CRR) MODEL

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1. INTRODUCTION

Interactive 3D virtual reality applications and tools for urban planning and design are usually either “silent” or with simple sound effects for audio projection. Handling correct spatial sound simulation is therefore a key factor for creating a convincing interactive audio-visual environment that will definitively improve the prospect of design and planning. However, the accurate real-time sound rendering of a multi-source dynamic urban soundscape is far beyond the capabilities of current techniques. On the other hand, the requirements for the acoustic simulation of urban spaces are relatively low compared to those for auditoria [1]. Therefore, simplifications in the acoustic simulation algorithms must be considered before developing an auralisation system. Some simplifications have already been proposed and examined in the previous studies of the authors [1,2]. It has been found that, for such environmental sounds like fountains and car noises, there is no significant perceptual difference in reverberation between soundtracks based on direct sounds only and direct plus reflected sounds [2]. However, for music and human voice, the effect of reverberation with a certain order of reflection has been found to be significant.

This paper focuses on the simplifications with respect to another physical phenomenon. While changes in diffusion coefficient of boundaries have been found to be clearly noticeable in room acoustics auralisation [3,4], the aim of this study is to evaluate the overall perceptual difference between auralised urban soundscape with purely specular, purely diffuse, and a mixture of specular and diffuse reflections from boundaries. This is studied using various spatial attributes.

The core of the auralisation system under development in this work is the CRR model, which combines ray tracing and radiosity models, allowing for modelling of different patterns of sound energy reflection. The detailed description of the CRR model, its implementation and validation can be found in references [5] and [6]. The auralisation process is carried out in the time domain, exploring digital signal processing and audio playback software, and hardware-based techniques.

This paper firstly deals with the perception of overall differences between auralised soundtracks which are proceeded with different boundary reflection patterns, considering a range of diffusion coefficients. A minimum audible difference caused by changing diffusion coefficient is identified. The second stage of experiments compares various spatial perceptual attributes between urban open spaces simulated with purely specular, purely diffuse and a mixture of specular and diffuse pattern of reflection in hypothetical rectangular urban squares of different dimensions. This is achieved by using music and human voice as source materials, with a fixed single source position. Finally, relationships between objective acoustic indices, including early decay time (EDT) and reverberation time (RT), and subjective attributes are studied using linear regression analysis.

It is expected that, based on the results of this study, considerable simplifications in acoustic simulations of urban open spaces and in auralisation can be made.

The paper starts with a brief overview of the auralisation system under development in this overall research project; it then describes the methodology and the results of experiments.

2. AURALISATION SYSTEM

The process of the auralisation system starts with the geometrical modelling of simulated urban spaces, which is also called scene modelling. The acoustic properties of the boundaries and the positions of sources and receivers are simply stored in the text-based scene files. The files also store the camera position, camera angle, light illuminations and other information for OpenGL implementation [7] for the scene visualisation purpose, as shown in Figure 1 in the Visual Rendering part.

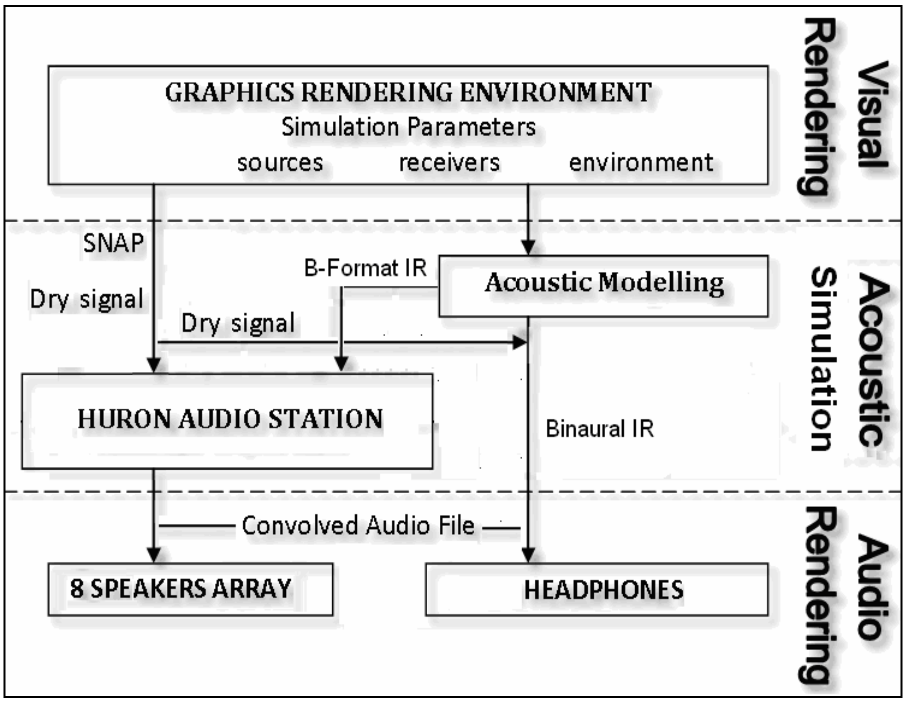


Figure 1. *Virtual auralisation system structure.*

The next part of the auralisation system is the acoustic simulation. The output of the acoustic modelling, realised with the CRR model, presents energetic impulse responses (IR), calculated in octave bands. An assortment of software-based DSP tools is then applied to obtain pressure impulse responses corresponding to CD quality, namely 16 bit resolution and 44.1kHz sampling frequency, or even higher quality with 32 bit and 48kHz.

Audio rendering and playback are realised via headphones, or an array of 8 loudspeakers through an Ambisonics system. For the former, the presentation of binaural impulse responses is obtained by filtering with head-related transfer function (HRTF). For the latter, the impulse responses are transformed into so-called B-format through an established algorithm. The B-format impulse responses are presented as 4 “channel” of wide-band pressure (W) and particle velocity (XYZ) components. The set of X, Y, Z and W signals represent a first-order approximation of the sound field at a given point in a space. Then, the obtained 4 impulse responses are normalised and processed with software and hardware based DSP tools.

The convolution of impulse responses with dry signals is the last process in both cases of auralisation. Binaural impulse responses convolved with dry signals are unified into binaural stereo .wav signal. B-format impulse responses are transformed into .sim format files of HURON workstation system that is used for convolution and further sound rendering [8]. The audio simulation rendered by HURON is linked to a graphical visualisation/simulation system via TCP/IP network and the Spatial Network Audio Protocol (SNAP).

3. METHODOLOGY OF SUBJECTIVE EVALUATION OF URBAN SOUNDSCAPE AURALISATION

3.1. Scene modelling

Three hypothetical urban squares of dimensions 25x25x20 (length x width x height) (Square A), 50x50x20 (Square B) and 100x100x20 (Square C) were modelled. The squares were open at the top, namely, with an absorption coefficient of 1. The boundaries including the ground were assumed to have the same absorption coefficients, which were estimated based on a mixture of glass and brick. Calculations with CRR program were performed in four octave bands, namely 125, 500, 2k and 4kHz, with absorption coefficients of 0.18, 0.15, 0.24 and 0.27, respectively. The air absorption was also determined at those frequencies, assuming a temperature of 10°C and relative humidity of 65%. Because the height is the same for all the three squares, in the description below only square length and width are referred to. An omni-directional sound source positioned in a corner and a receiver in the middle of each square, was considered. The source and receiver heights were 1.2m and 1.5m above the ground, respectively.

3.2 Source materials

Two environmental sounds, music (flute/guitar) and human voice (male speech), were chosen as the source materials for auralisation. The dry signals were mono 16-bit and 44kHz sampling resolution .wav files recorded in an anechoic chamber. For auralisation, the dry signals were convolved with impulse responses calculated with CCR, resulting into test samples of 10 to 15 seconds in duration.

3.3. Subjective tests

The paired comparison listening test, also called A/B test [9], with a 5 point scale, both verbal and numerical, was utilised. This method has been commonly used in subjective evaluation of auralisation systems [10]. The evaluation task in A/B test took the form of a 2 interval forced choice where the subjects compared two samples presented one at a time in two successive intervals, with the order of presentation varying randomly from trail to trail.

The listening test was carried out in two stages. The first experiment (Experiment I) studied whether listeners were able to distinguish differences between soundtracks based on CRR modelling results with diffusion coefficients 0, 0.1, 0.2, 0.5 and 1, where 0 represents purely specular reflection pattern, 1 represents purely diffuse one and other coefficients present various mixture of specular and diffuse patterns. The tested null statistical hypothesis was that there was no audible difference between reflection models. The impulse responses calculated for Square B were used in this test. The subjects, after listening to the signals, were asked to judge the overall difference between the signals, with an answer sheet, as shown in Figure 2.

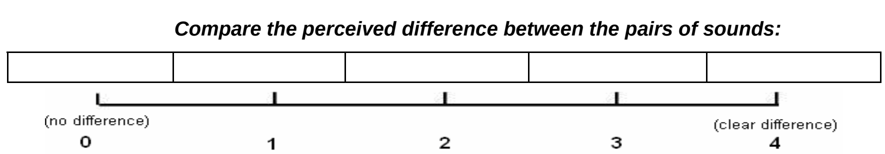
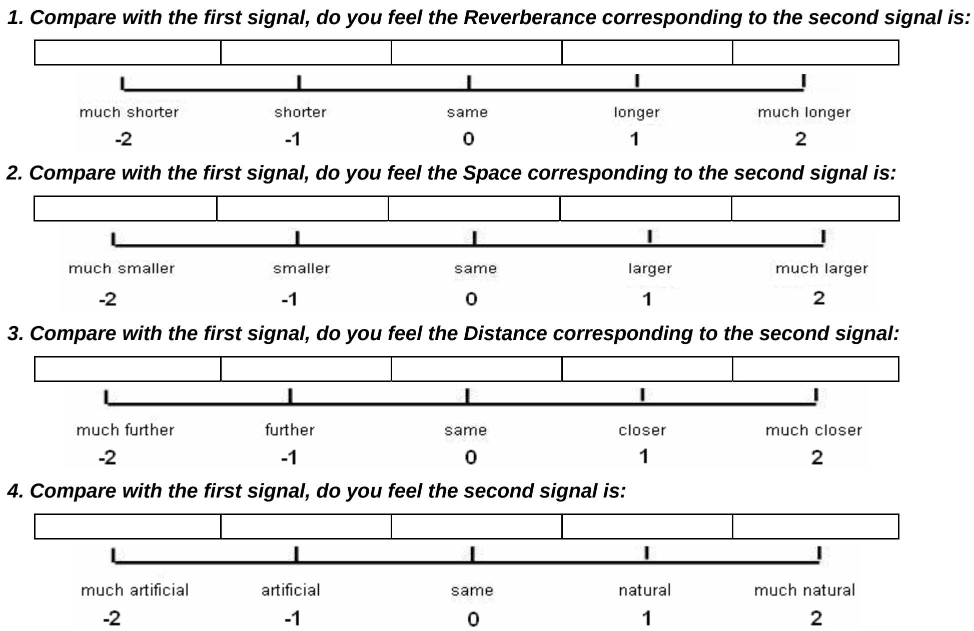


Figure 2. *The evaluation sheet used in Experiment I.*

The second experiment (Experiment II) was conducted in order to find out the nature of the differences between reflection models, so a number of subjective spatial attributes was used, including the feeling of Reverberance, Space, Distance and Naturalness. Those subjective attributes heavily depend on the form of impulse responses for which the consideration of boundary diffusion is vital. While in ray tracing an inherent problem is the simplification in diffusion, CRR is more appropriate in this case. A diffusion coefficient of 0.1 [11] was selected for modelling the mixed specular and diffuse reflections. Square A, B and C were all used for this stage of the experiment. The tested null statistical hypothesis was that the reflection model has no effect on the judgment of the spatial attributes. In this test, the subjects, after listening to the pair of the signals based on different reflection models, were asked how the second signal, compared to the first one, providing a different sensation of a subjective attribute. Figure 3 shows the evaluation sheet. A subject was asked to answer one question at a time, then the same pair of signals was played again and the question about the next spatial attribute was asked.



1. Compare with the first signal, do you feel the Reverberance corresponding to the second signal is:

much shorter	shorter	same	longer	much longer
-2	-1	0	1	2

2. Compare with the first signal, do you feel the Space corresponding to the second signal is:

much smaller	smaller	same	larger	much larger
-2	-1	0	1	2

3. Compare with the first signal, do you feel the Distance corresponding to the second signal:

much further	further	same	closer	much closer
-2	-1	0	1	2

4. Compare with the first signal, do you feel the second signal is:

much artificial	artificial	same	natural	much natural
-2	-1	0	1	2

Figure 3. *The evaluation sheet used in Experiment II.*

Six inexperienced (naïve) listeners, aged from 22 to 30, were used in both experiments. All of them reported normal hearing. The choice of naïve listeners was suggested by Begault [12] for A/B type of tests. However, all participants underwent a training session before each test. The whole test set, including Experiment I and II, contained 32 pairs of test signals. The subjects were free to playback the test signals as many times as they felt was necessary. The overall duration of the two experiments was around 30 minutes. The tests were only carried out using headphones, which were Sennneiser HD 590.

The analyses of the test results were performed with software SPSS 14.0. 0.05 chance of making an error (confidence interval) was applied for rejecting the null hypotheses.

4. EXPERIMENT RESULTS

4.1. Experiment I

Descriptive statistical parameters have been calculated for each pair of the tested signals. The two tail *t*- test has been applied to study the significance of perceptual difference between mean values within each pair of signals and 0 (no differences between signals). Table 1 summarises the calculated parameters. The means and standard deviations are also shown in Figure 4.

The results of the experiment show that for music the 0-0.1 and 0-0.5 pairs provide the highest mean values of difference. Both of them are statistically significant. The lowest mean value has been found for the pair 0.1-0.2. Moreover, this difference is not significant.

For human voice the highest mean difference is obtained for the 0.1-1 pair and also the 0-0.5 pair. The differences for both these pairs are significant. Compared to music, for human voice there are no significant differences for the 0.1-0.5 and 0.5-1 pairs. Instead, the difference for the 0.1-0.2 is significant.

The standard deviations for human voice pairs are generally higher than for music, which might indicate that subjects have more difficulties in judging the differences between reflection models for human voice pairs.

Some listeners indicated that it was difficult to give exact numerical differences. It seems that a 3 point scale might be more appropriate for certain test pairs.

Table 1. *Mean difference, standard deviation (STD) and significance level (Sig.) between various boundary diffusion coefficient pairs, using music and human voice.*

Pair	Music			Human voice		
	Mean	STD	Sig.	Mean	STD	Sig.
0-0.1	2.200	0.837	0.004	1	1	0.009
0-0.5	2.330	0.816	0.001	2.33	0.516	0.000
0.1-0.2	0.500	0.548	**0.076**	1.330	1.211	0.043
0.1-0.5	0.830	0.408	0.004	1.330	1.366	**0.062**
0.2-0.5	0.830	0.753	0.042	1.830	1.169	0.012
0.5-1	1.000	0.894	0.041	0.500	0.548	**0.076**
0.1-1	1.400	0.894	0.024	2.800	1.304	0.009

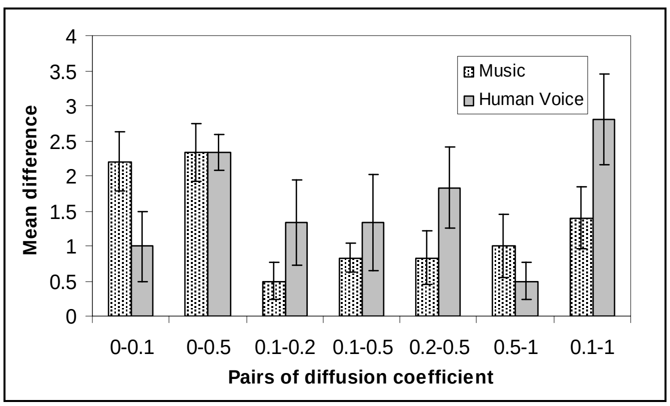


Figure 4. *Mean difference between various boundary diffusion coefficient pairs, using music and human voice, where the standard deviations (STD) are also shown.*

4.2. Experiment II

The two tail *t*-test has been again applied to test the significance of the difference in subjective attributes between mean values and 0. Descriptive statistical parameters have been also calculated. The results are given in Table 2 and Figure 5.

It can be seen that for music, in the 0-1 pair, the second signal provides the feeling of shortest Reverberance and the closest Distance between the source and the receiver compared to the other pairs of signals. This means that the highest differences in these subjective attributes are audible between purely specular and purely diffuse reflections. The difference in the feeling of Space is the highest for the 0-0.1 pair. In terms of the feeling of Space and Distance, the difference is rather small between the 0.1-1 pair. The feeling of Naturalness is much more different for the 0.1-1 pair, with the second signal being more artificial. In other words, this result suggests that music based on purely diffuse reflection may not sound natural in comparison to simulations based on a mixture of specular and diffuse reflections, although in Table 2 this difference is not at a statistically significant level. For the 0-0.1 pair, the feeling of Naturalness is similar, so as for Reverberance.

In the case of human voice, the pair 0-1 provides the highest negative difference in the feeling of Reverberance and Space and highest positive difference in the feeling of Naturalness. The highest positive difference in the feeling of Distance has been found between the 0.1-1 pair. The lowest difference in all the attributes is for the 0-0.1 pair.

Table 2. *Mean difference, standard deviation and significance of difference in subjective attributes between various boundary diffusion coefficient pairs, using music and human voice.*

	Music			Human voice		
Pair	Mean	STD	Sig.	Mean	STD	Sig.
			Reverberance			
0-0.1	-0.278	0.958	**0.235**	-0.722	1.127	0.014
0-1	-0.667	0.907	0.006	-1.444	0.705	0.000
0.1-1	-0.500	1.098	**0.070**	-1.222	0.808	0.000
			Space			
0-0.1	-0.444	0.922	**0.057**	-0.556	1.199	**0.066**
0-1	-0.278	1.018	**0.263**	-1.222	0.878	0.000
0.1-1	-0.222	0.878	**0.298**	-1.167	1.150	0.000
			Distance			
0-0.1	0.556	0.784	0.008	0.000	1.029	**1.000**
0-1	0.667	0.840	0.004	0.944	1.259	0.005
0.1-1	0.333	0.686	**0.055**	1.222	1.003	0.000
			Naturalness			
0-0.1	0.056	0.938	**0.804**	0.222	1.215	**0.448**
0-1	0.167	1.150	**0.547**	0.556	1.247	**0.076**
0.1-1	-0.267	0.799	**1.000**	0.223	1.309	**0.481**

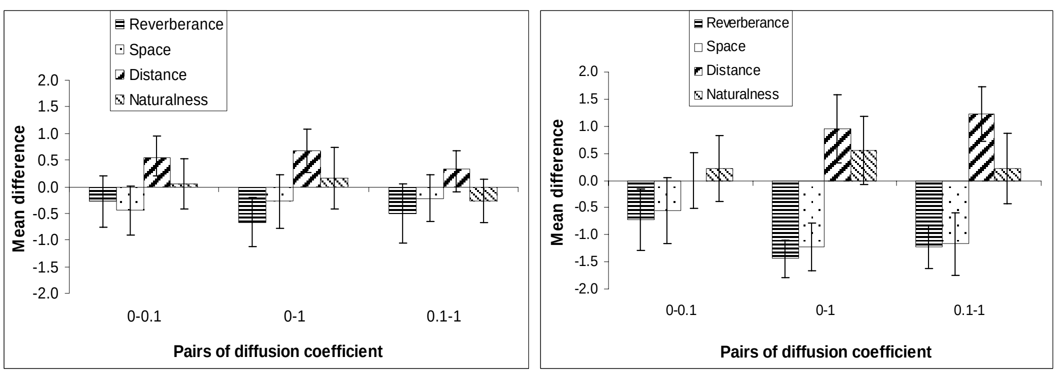


Figure 5. *Mean differences in subjective attributes between various boundary diffusion coefficient pairs, using music (left) and human voice (right), where the standard deviations (STD) are also shown.*

It is also interesting to note that there are some notable differences between music and human voice. For music, in terms of Reverberance the difference is only significant for the 0-1 pair, while for human voice the difference is significant for all pairs. In terms of the feeling of Space, for music no significant difference is shown for any pairs, whereas for human voice no significant difference is found for the 0-0.1 pair. For the feeling of Distance and Naturalness there are also noticeable differences between music and human voice in terms of mean values, although in terms of significant level the difference is less.

In order to examine the overall difference in subjective attributes between music and human voice, the results are averaged over all pairs, as shown in Figure 6. It can be seen the averaged mean values for human voice are generally greater than those for music. Indeed, following the test, most participants reported that they found much more difficult in discriminating subjective attributes of music signals compared to human voice. Differences between different sounds have also been reported by Lokki *et al* [10], who found distinguish perceptual differences in spatial subjective attributes of drum sound (wide-band transient signal) between simulated and recorded soundtracks, compared to other music sounds.

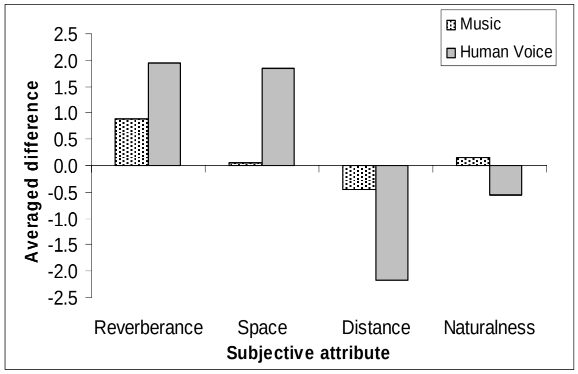


Figure 6. *Averaged differences of all pairs showing the difference between music and human voice.*

The differences in subjective attributes between models of reflection have also been studied as a function of dimension of simulated urban spaces, and the results are shown in Figure 7. It is interesting to note that for the feeling of Reverberance, Space and Distance, the difference caused by changing diffusion coefficient generally becomes greater with the increase in square size. With a given change of diffusion coefficient, within a larger square, subjects feel that Reverberance is less, Space is smaller, and the Distance is closer. For Naturalness the variation with square size is not systematic.

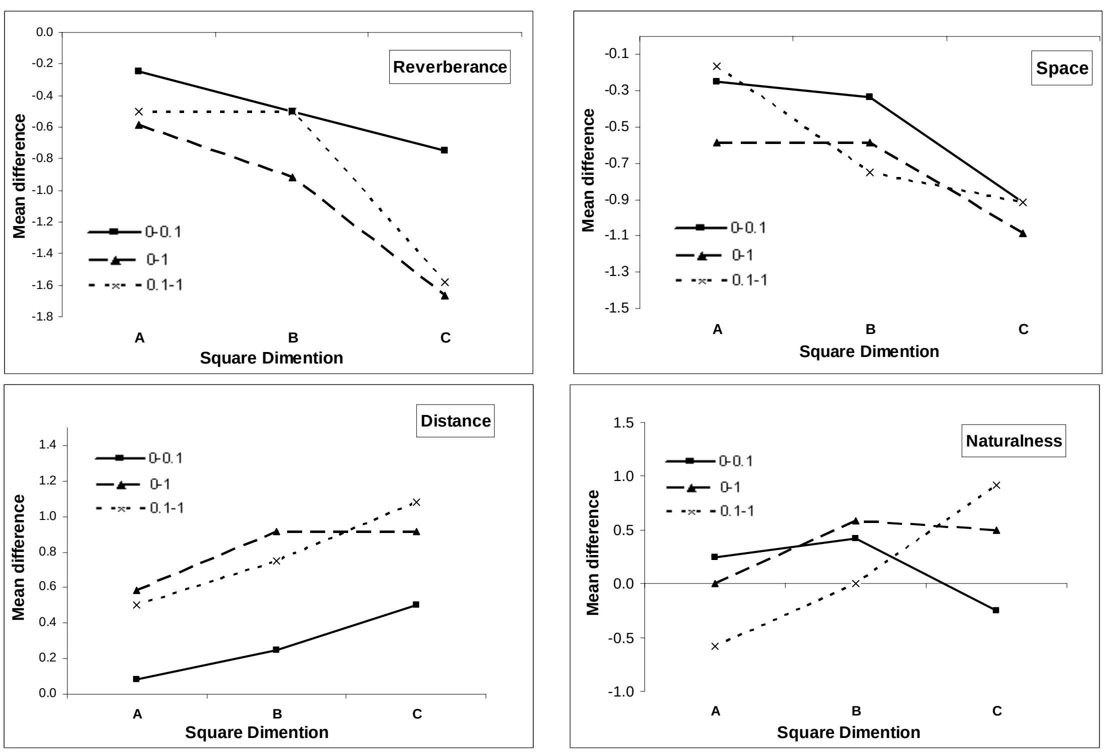


Figure 7. *Variation of the mean differences in subjective attributes caused by changing diffusion coefficients with increasing square dimensions.*

5. RELATIONSHIPS BETWEEN SUBJECTIVE ATTRIBUTES AND OBJECTIVE INDICES

In order to examine the influence of objective acoustic indices of analysed soundscape on the studied subjective spatial attributes, EDT and RT have been calculated with CRR model. While these indices have been found to be very important in people's sensation of reverberation in indoor environments, little however is known about their effects in outdoor soundscapes. Table 3 presents the EDT and RT in 4 typical octave bands for the 3 studied urban spaces, where 3 diffusion coefficients are considered.

To perform statistical analysis, subsequent subtractions in objective indices are made for each pair of diffusion coefficients, as shown in Table 4. It can be seen that the highest differences in objective indices are generally found between diffusion coefficients 0 and 1, and the lowest differences are between diffusion coefficients 0 and 0.1. The differences increase with increasing square dimension.

Table 3*. EDT and RT for 3 squares at 4 octave bands, with 3 diffusion coefficients.*

Square	Model	0			0.1			1			0		
	Freq.	125			500			2000			4000		
A	EDT	1.26	1.26	0.90	1.44	1.26	0.90	0.90	0.90	0.72	0.72	0.90	0.72
	RT	2.99	2.02	0.82	3.48	2.20	0.86	1.97	1.46	0.72	1.45	1.13	0.64
B	EDT	2.88	2.34	1.80	3.06	2.52	1.80	1.80	1.62	1.44	1.08	1.26	1.26
	RT	5.97	3.79	1.54	6.59	4.18	1.61	3.23	2.51	1.30	2.20	1.85	1.12
C	EDT	3.96	3.60	1.80	4.68	3.60	1.80	2.52	2.34	1.44	0.72	0.90	1.08
	RT	13.3	8.27	2.09	13.8	8.57	2.17	5.35	3.40	1.79	2.84	2.40	1.50

Table 4*. Difference in EDT and RT between diffusion coefficients, for 3 squares at 4 octave bands.*

	Freq.	125			500			2000			4000		
Square	Model	0-0.1	0-1	0.1-1	0-0.1	0-1	0.1-1	0-0.1	0-1	0.1-1	0-0.1	0-1	0.1-1
A	ΔEDT	0.00	0.36	0.36	0.18	0.54	0.36	0.00	0.18	0.18	-0.18	0.00	0.18
	ΔRT	0.97	2.17	1.20	1.28	2.62	1.34	0.51	1.25	0.74	0.32	0.81	0.49
B	ΔEDT	0.54	1.08	0.54	0.54	1.26	0.72	0.18	0.36	0.18	-0.18	-0.18	0.00
	ΔRT	2.18	4.43	2.25	2.41	4.98	2.57	0.72	1.93	1.21	0.35	1.08	0.73
C	ΔEDT	0.36	2.16	1.80	1.08	2.88	1.8	0.18	1.08	0.9	-0.18	-0.36	-0.18
	ΔRT	5.03	11.21	6.18	5.23	11.63	6.4	1.95	3.56	1.61	0.44	1.34	0.9

The linear regression analysis has then been applied to find out the correlation coefficients between objective indices and subjective attributes, as shown in Table 5. The significance of correlation is also pointed out. An absolute value of 0.3 was chosen to represent a sufficient correlation.

Table 5*. Correlation coefficients and the significance of correlation between the differences in objective indices and differences in subjective attributes caused by increased diffusion coefficient, based on the data in 3 squares and 3 pairs of diffusion coefficient changes*.

Freq.	Index/ Attribute	Reverberance		Space		Distance		Naturalness	
		Correlation	Sig.	Correlation	Sig	Correlation	Sig.	Correlation	Sig.
125	ΔEDT	-0.766	0.012	-0.823	0.004	0.678	0.035	0.339	**0.342**
	ΔRT	-0.803	0.006	-0.869	0.002	0.721	0.021	0.371	**0.294**
500	ΔEDT	-0.951	0.000	-0.820	0.006	0.635	**0.066**	0.544	**0.130**
	ΔRT	-0.913	0.000	-0.800	0.008	0.574	**0.106**	0.494	**0.177**
2k	ΔEDT	-0.754	0.014	-0.812	0.006	0.660	0.041	-0.298	**0.407**
	ΔRT	-0.814	0.005	-0.874	0.001	-0.750	0.015	0.430	**0.219**
4k	ΔEDT	-0.640	0.050	0.684	0.033	0.545	**0.109**	0.165	**0.650**
	ΔRT	-0.788	0.008	-0.827	0.004	-0.731	0.019	0.413	**0.239**

The results demonstrate the good correlation between objective indices and subjective attributes. However, the correlation is significant for all frequency bands only in terms of the feeling of Reverberance and Space. In the case of the feeling of Distance, it is not significant at 500Hz for both objective indices, and at 4kHz for EDT. For the feeling of Naturalness, the correlation is not significant at any of the octave bands. It is noted that, at octave bands 125, 500 and 2kHz, the correlation coefficients between EDT and the subjective attributes are only slightly different from that for RT, while at 4kHz the values of correlation coefficient are higher for RT than for EDT, by about 0.2. This is somewhat different from the situation in room acoustics, where EDT plays a more crucial role in perception of reverberation.

It is also interesting to examine whether there are any relationships between various subjective attributes. The results of such an analysis are shown in Table 6. It can be seen that good correlation exists between Reverberance and Space, Reverberance and Distance and between Space and Distance that confirms the results presented above. The first three attributes are less correlated with Naturalness. Moreover, the correlations between Naturalness and Space and between Naturalness and Distance are not significant. It is possible that Naturalness is controlled more by other objective measures.

Table 6*. Correlation coefficients and the significance of correlation between subjective attributes, based on the data in 3 squares and 3 pairs of diffusion coefficient changes*.

Attribute	Reverberance		Space		Distance		Naturalness	
	Correlation	Sig.	Correlation	Sig	Correlation	Sig.	Correlation	Sig.
Reverberance	-	-	0.960	0.000	0.930-	0.000	0.648	0.047
Space	0.960	0.000	-	-	0.950	0.000	0.578	**0.084**
Distance	0.930	0.000	0.950	0.000	-	-	0.501	**0.145**
Naturalness	0.648	0.047	0.578	**0.084**	0.501	0.145	-	-

6. DISCUSSIONS AND CONCLUSIONS

The aim of this paper was to evaluate through subjective tests the overall perceptual differences and the difference in subjective attributes between auralised urban soundscapes with purely specular, purely diffuse and a mixture of specular and diffuse boundary reflection patterns. Three urban squares have been considered, with both music and human voice signals.

In terms of the overall perceptual differences, for both music and human voice, the differences are significant between purely specular and purely diffuse boundaries, whereas between various mixture of specular and diffuse patterns of reflection the differences are relatively less. For music, the subjective perception for models with a relatively small diffusion coefficient of 0.1 has been found to be rather close to that with purely diffuse boundaries, namely with diffusion coefficient of 1. This indicates a possible way of simplification in urban space auralisation.

With regards to sound quality, the results suggest that purely specular pattern of reflection gives the feeling of the longest Reverberance and the largest Space, purely diffuse one gives the feeling of the shortest Distance between the source and receiver, while a mixture of reflection patterns provides more Natural feeling of the auralised soundscape. It has been also found that the increase of diffusion coefficient from purely specular reflection to a mixture of specular and diffuse reflection, as well as from purely specular reflection to purely diffuse reflection, provides an increase in the feeling of Naturalness. Generally speaking, no systematic differences have been found between a mixture of specular and diffuse reflection and purely diffusion reflection.

The average mean of differences in subjective attributes appeared to be lower for music than for human voice. It again confirms that simplifications in acoustic modelling for auralisation with music signals will be much more perceptually acceptable than that with human voice.

It is interesting to note that between objective indices including EDT and RT and studied subjective attributes there are good correlations. The highest correlation is generally found between the objective indices and the feeling of Reverberance and Space, whereas the feelings of Distance and especially Naturalness are less correlated with the objective indices.

While the results in this paper already suggest the possibility of simplifying the acoustic modelling to achieve faster interactive real-time auralisation for aiding urban soundscape design, it is noted that these tests were performed with a single source. In a dynamic multi-source environment the differences found in this study might be even less, which is useful for further simplifications. This is the subject of further investigations, utilising a 3D audio-visual virtual reality system of urban environment, which is currently being developed.

Given the above differences, it would be important to compare simulated and measured soundscapes, for which some initial results are reported in a parallel paper [13].

7. ACKNOWLEDGEMENTS

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