Potential of Reverberation in Squares for Soundscape Perception

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Summary
Reverberation is a well-known acoustic factor for architectural design. The idea of appropriate and diverse reverberation times along baroque enfilades (a specific series of rooms in manor houses) served as an inspiration to investigate if similar perceived quality can be achieved in open spaces. The sequence of public spaces in Zagreb, Croatia, was chosen for the initial stage of this study. Reverberation time was measured using firecrackers as impulse sound sources. The measured values clearly supported the idea of a spatial sequence within a span from public to intimate. However, in recorded scenarios, analyses of soundscape perception descriptors, showed that other factors, such as traffic noise, probably cancelled the hypothetical effect of diverse reverberation times. Further research was conducted on a morphologically different but acoustically comparable sequence of public spaces in Sheffield, United Kingdom, to investigate factors that make reverberation in open space more significant for the overall assessment. The research includes a total of 17 squares, 8 in Zagreb and 9 in Sheffield, which were assessed using similar methodology on both locations. Spherical photographs and three-dimensional audio recordings were made to serve as a basis for listening experiments conducted in auralisation laboratory using tools for virtual reality simulations. It is expected that further research would show which features are most significant for the perceptibility of the investigated concept.

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1. Introduction

The aesthetic aspect of reverberation is usually considered from the musical viewpoint. It is a question of adding a reverb effect to a sound source during a process of mixing a musical piece, or a question of tailoring reverberation time which would suit musical style expected to be performed in a room. It also forms an important part of integral architectural aesthetics [1], if aesthetics is considered a theory of sensual perception [2]. However, there is an open question about which approaches apply in that case and particularly which approaches apply in open spaces.

In cases where the discourse of architectural theory considers acoustics, it often observes functional and aesthetic values of reverberation. Norberg-Schultz [3] considered aesthetic requirements (in general) equally important as the functional requirements, while Böhme [2] suggested that soundscape aesthetics should be 'ecological aesthetics' – 'natural rather than artificially designed' and 'ecologically important'. Brown [4] suggested, similarly to Rasmussen [5] that the key

to aesthetically pleasing overall ambience is the congruence between all sensory layers.
The congruence between the aural and visual experience, or the aural appropriateness to visual and functional features [5] can therefore be considered also as the key for the urban reverberation aesthetics. While the functional value of reverberation can be quantitatively assessed by measuring indicators such as speech intelligibility (in spaces which serve a function dependent on spoken communication), evaluating appropriateness is a far vaguer concept, both quantitatively and qualitatively [6] [7]. However, both types of values have an equally significant role in design, especially if considered from the viewpoint of soundscape research, which cherishes a holistic approach to the sound environment.
The architectural concept of the baroque enfilade (a specific series of rooms in manor houses) stands as a paradigm of integral design, characterised by congruence between functional and aesthetical – both visual and aural, both design and function [5]. From a mansion entrance, a sequence of rooms begins with a marble hall, followed by a large dining-room, a salon with silk-panelled walls suitable for chamber music, then a smaller room, until it ends in a satin-lined boudoir suitable for whispered trysts [5]. Aesthetical appropriateness in this case remains an open question since Rasmussen [5] relied on intuitive criteria based on the main activity imagined within a specific space and visual and acoustical properties of materials used.
Since that time, many tools for qualitative analysis of acoustic properties have been developed [10] [11]. Urban sound design tools were also considered in valorisation, such as adding water sound sources [12], electroacoustic sound sources [13] or choosing materials which influence both the creation of sound and its diffusion, such as foot paths materials [14]. From a soundscape approach, it is again interesting to note that reverberation is sometimes left out, hence including sound sources in the discourse on aural aesthetics of the environment [16]. From the viewpoint of landscape theory Hedfors interpreted reverberation as a part of a ‘resonating landscape’, and all sound sources within a landscape as a ‘generating landscape’ [17].
Regarding the design of squares and reverberation, researchers recognised the importance of urban form for articulation of early reflections which influence perceived loudness and sound clarity [17].
Previous studies showed that introducing musical sound sources in public space can significantly shift perception of the environment towards a more positive assessment [18], sometimes comparatively diminishing the soundscape appropriateness in relation to visual features [8].
An integral approach to soundscape aesthetics which would encompass spatial acoustics, sound sources and users in all the complexity and still be accessible to urban design and planning practice is yet to be developed. Following the previous study conducted by the authors [17] [18], the idea of appropriate and diverse reverberation times along a baroque enfilade served as an inspiration to investigate if a similar perceived quality can be achieved in open spaces. This research aims to further investigate key factors for perceptibility of the architectural concepts which contribute to aesthetic quality of reverberation in public spaces.

2. Methodology

The sequence of public spaces in Zagreb, Croatia, was chosen for the initial stage of this study as it was considered that it can represent the idea of a spatial sequence within a span from public to intimate in terms of activity, acoustical and visual features. Two squares in Sheffield characterised by very different physical features were chosen for the second part of the study.
The research activities regarding all locations included field measurements for quantitative software analyses (reverberation time, sound pressure level and speech intelligibility) and audio-visual recordings for qualitative analyses (soundscape perception descriptors), as listening experiments followed. At each square, the same measurement points were used for all activities following one measurement points per square principle.
Reverberation time at the locations in Zagreb was measured using firecrackers as impulse sound sources, while in Sheffield balloons were used.
Listening experiments have so far been conducted in the loudspeaker equipped auralisation laboratory for the Zagreb recordings and using headphones for the Sheffield recordings.

2.1. The sequence of public spaces in Zagreb, Croatia

The sequence of public spaces in Zagreb, Croatia, consists of several adjacent squares of the

approximately the same area size (approximately 2,2 ha with and 1,7 ha without the area of the streets positioned along the square), all characterised by a very similar rectangular shape, as described by the authors [8] [9]. Seven squares and one park are forming a continuous sequence of a horseshoe-like shape. Therefore, eight measurement points were chosen, each corresponding to one public space, consequently labelled as Z1-Z8 starting from the north-west square (Z1), following the horseshoe shape to the south (Z4), then to the east (Z5) and ending at the north-east one (Z8).
The sequence is part of the historical city centre, built in the second part of the 19th and the beginning of the 20th century. Not all squares in the sequence are being adequately used in terms of their potential [19] [8] [20].
Due to different buildings built within the squares, it was expected that each square will be characterised by different reverberation time, appropriate to its use and visual features.
Water sound sources were present at three locations in Zagreb, while other sound sources included traffic noise, passers-by stepping and chattering and bird songs, as observed by researchers.

2.2. Case study sites in Sheffield, United Kingdom

Two squares with two corresponding measurement points along the 'Gold Route' in Sheffield were selected and investigated as separate public spaces (although they are a part of a sequence/route), to further illustrate the issue: Peace Gardens (0,9 ha, labelled S2) and Leopold Square (0,1 ha, labelled S4). Different in size and shape, they both contain water features that mask traffic noise. Other sound sources included traffic noise, ventilation noise, passers-by stepping and chattering and bird songs, as observed by researchers.
Other seven squares located at the 'Gold Route', investigated within the broader study, are not described in this paper.

2.3. Firecrackers and medium sized balloons as impulse sound sources

The impulse sound sources used for measurements can be categorised as grade 2 firecrackers and medium-sized balloons corresponding to the categorisation suggested by Horvat, Jambrošić and Domitrović [21]. Only the upper part of the spectrum (above 500 Hz) was considered in the analyses since both sources do not offer adequate excitation level at the low end of the spectrum [21] and because the signal to noise ratio is too small for octave frequency bands below 500 Hz.

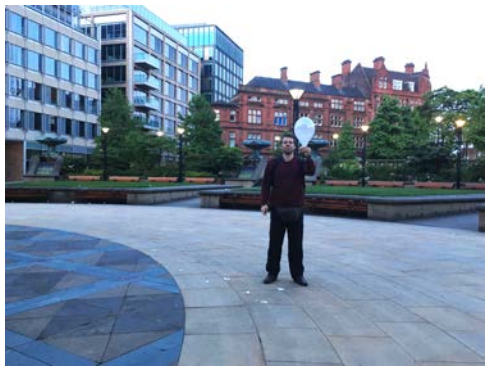

Figure 1. Measurements in June 2017 at Peace Gardens, Sheffield.

Reverberation times at all locations were measured during early morning hours (between 4:30 and 7:30 A.M.) to achieve optimum signal to noise ratio.
As grade 2 firecrackers can produce a peak sound pressure level of 162,9 dB at 1 m [21], the measurements in Zagreb were performed during the festive days of New Year 2017, when noise from pyrotechnics is allowed by law.
Impulse sound sources at both locations were recorded using Neumann KM 183 omnidirectional pattern microphone, Apogee One preamplifier and analogue to digital audio converter and iPad 3. The microphone and the preamplifier were previously calibrated in an anechoic chamber.
The omnidirectional directivity pattern microphone was positioned approximately 10 m from the firecrackers and 5 m from the balloons. Measurement points were selected in the central area of each square to capture its most recognisable features and impulse response pattern, as considered by the authors.

2.5. Listening experiments

Soundscapes used for listening experiments were recorded at the exact measurement points during early afternoon hours to capture soundscape created by everyday city life.
Listening experiments using Zagreb recordings were conducted in December 2014 and March 2017 in auralisation laboratory equipped with sixteen loudspeakers capable of reproducing spatial ambisonics recordings. Thirty-five participants in 2014 and another twenty in 2017, mainly under and post graduate students, contributed to this study. This paper is focused on the results of the experiment conducted in 2014 as the one conducted

in 2017 included sound sources which significantly changed soundscape perception.
Listening experiments using Sheffield recordings were conducted in June 2017 in a quiet environment using headphones and mono soundscape recordings. Ten participants, mainly post graduate students, took part at this stage.
The conducted listening experiments were performed using the same questionnaire based on the Swedish Soundscape Quality Protocol.

3. Results and discussion

The results of measurements and partial results of the so far conducted listening experiments, presented in this paper, are focused on participants' comments.

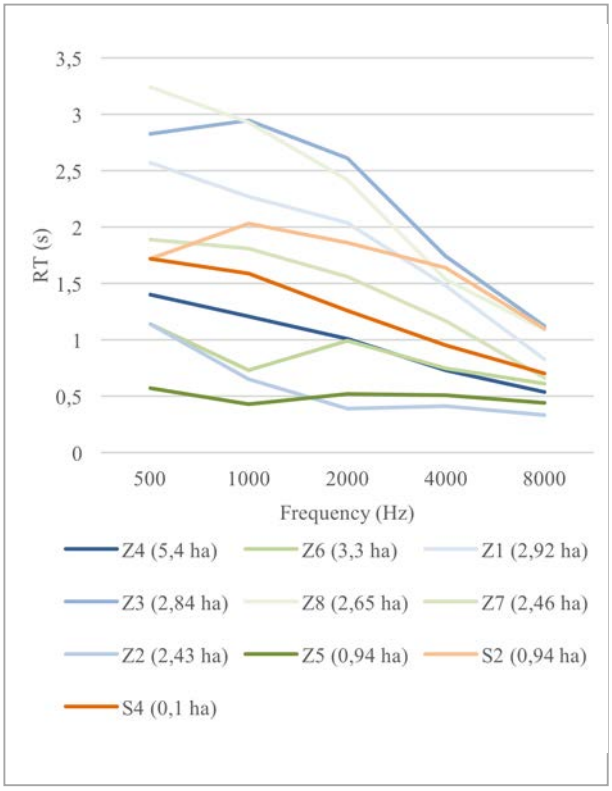

Figure 2. Measured reverberation times at locations in Zagreb and Sheffield per frequency bands.

3.1. Measured reverberation values

Firecrackers proved to be a more adequate sound source for open space measurements than the balloons, as expected. The balloons did not provide enough excitation in the low frequency band to enable precise measurements. However, it was considered that this does not influence the main purpose of the study, which was to detect the spatial character in the most perceptible frequency band (for reverberation). Consequently, only frequency bands above 500 Hz were considered.
The measured values in Zagreb, spanning from 0,87 s to 3,07 s at 500 Hz, supported the initial concept of a spatial sequence characterised by diverse reverberation times, despite the similar size and shape of individual squares.
The measured values in Sheffield fitted within the span measured in Zagreb.

3.2. Soundscape perception values and sound source types

The analysis of soundscape perception descriptors showed that the initial idea is not perceptible or that it does not significantly contribute to the overall soundscape quality. Figure 3 shows the soundscape perception values for the sequence in Zagreb, featured in a previous study [8]. The listening experiment proved the perceived dominance of the traffic noise which contributed to ambiguous values of the soundscape perception descriptors.

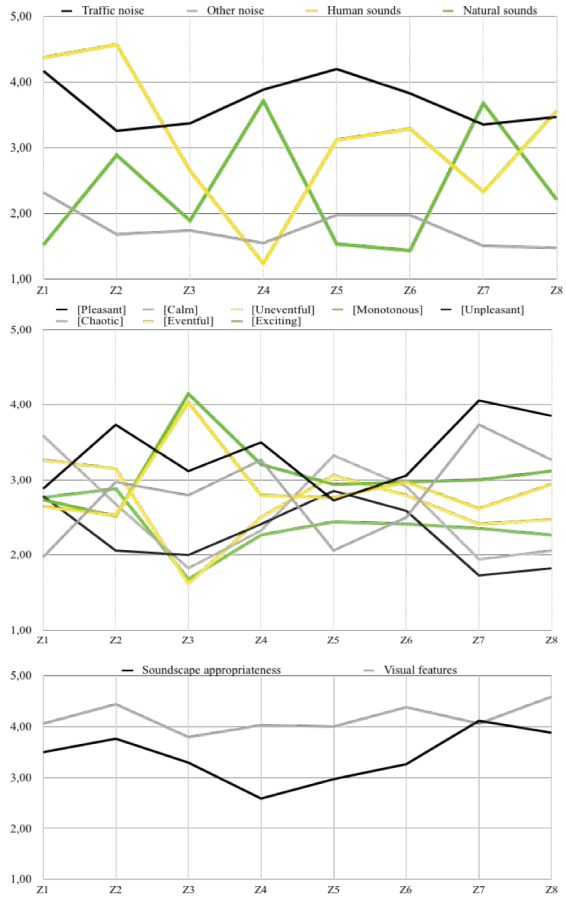

Figure 3. From top to bottom: dominance of sound source types, soundscape perception descriptors and soundscape appropriateness for the Zagreb case.

The participants rarely commented within the questionnaire form, which makes the comments even more significant. All participants were aware that the research was about soundscape perception but they were given no further details on the research focus.
The participants mainly addressed the sequence in Zagreb as 'unexpectedly noisy' stating:
'This square is completely surrounded by traffic, and there's no buffer.' (Z1)
'Traffic noise is just too much, this is the city centre.'(Z1)
'I can hardly hear natural sounds, traffic noise and other noises are dominant.'(Z1)
'There's not much other sounds besides traffic sounds.'(Z3)
'The traffic noise is dominant. It's so monotonous, it's hard to hear other sounds.'(Z3)
'This is a park, traffic noise is too loud.'(Z2)
'I wish there would be less traffic noise.'(Z2)
'Although this is a botanical garden, the traffic sounds are dominating, natural sounds seem weak.'
In Zagreb, average 16% participants per measurement point chose to comment within the questionnaire, 75% of which mentioned traffic noise, 82% of which commented on its inappropriateness.

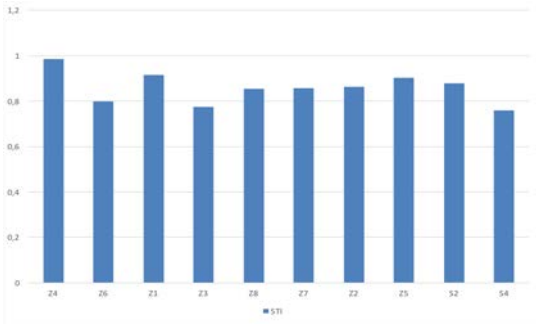

Figure 4. Speech transmission index at the locations in Zagreb and Sheffield. From left to right – squares by their area size.

On the other hand, the Leopold Square in Sheffield prompted observations on reverberation (67% of the comments at this measurement point), possibly related to perceived loudness influenced by early reflections:
'isolated square where the sound from people walking is reverberating'(S4)
'I would have expected more sounds of people talking and eating etc. and didn't expect footsteps to be so loud and clear'(S4)
'sound coming from paving where people walk is feeling urban architectural.'(S4)
'Just have a normal feeling about this place. Look like a normal eating area. The sound of the footstep really loud.'(S4)
In Sheffield, average 55% participants per measurement point chose to comment within the questionnaire, 18% of which mentioned traffic noise (none at Leopold Square), while no participant commented on its inappropriateness.

4. Concluding remarks

Measured reverberation times in Zagreb showed values which supported the initial concept. However, the listening experiments indicated that the investigated acoustic quality of the Zagreb sequence did not significantly influence soundscape quality. Its soundscape appropriateness was assessed as poor and perception descriptor values were ambiguous. This is most probably due to the traffic noise being the most prominent sound source type along the sequence, as indicated by the amount of the participants who commented on its inappropriateness. Positioning measurement points in the central part of each square, further from roads did not mitigate this effect.
During the assessment of the smallest investigated square – Leopold Square in Sheffield, participants decided to comment on the reverberation and its effect on the overall ambience. Comments addressed reverberation either directly or by describing the effect of early reflections on clarity and perceived loudness.
Despite the comments which revealed clear difference in soundscape perception between the Zagreb and Sheffield cases, the measured reverberation times and speech transmission index values didn't indicate any correlation with the investigated perceptive quality. While the comments showed that reverberation can be perceived and recognised as a quality feature of urban open space, this study indicated that the dominance of the traffic noise is the most distinguishable factor diminishing its perceptibility.

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