A Reverberation Instrument Based on Perceptual Mapping

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ABSTRACT

The present article describes a reverberation instrument which is based on cognitive categorization of reverberating spaces. Different techniques for artificial reverberation will be covered. A multidimensional scaling experiment was conducted on impulse responses in order to determine how humans acoustically perceive spatiality. This research seems to indicate that the perceptual dimensions are related to early energy decay and timbral qualities. These results are applied to a reverberation instrument based on delay lines. It can be contended that such an instrument can be controlled more intuitively than other delay line reverberation tools which often provide a confusing range of parameters which have a physical rather than perceptual meaning.

Keywords

Reverberation, perception, multidimensional scaling, mapping

1. INTRODUCTION

Reverberation is ubiquitous as an audio effect, yet its musical potential is seldom fully realized. Reverberation is more than just smearing a signal in time, it can also convey a context to sounds, which can be fascinating especially in electro-acoustic music. A reverberation instrument to investigate its potential is needed, which allows control of spatiality based on perceptive qualities, rather than a multitude of physical parameters. In this paper, different techniques for artificial reverberation will be weighed against each other. On the basis of psychoacoustic research, an instrument for intuitive control of reverberation will be proposed.

2. CHALLENGES IN ARTIFICIAL REVERBERATION

Reverberation can be considered as a series of repetitions of a signal, as caused by sound reflection from walls and obstacles. As such, there are various ways of artificially reverberating a signal, which can be roughly divided into impulse response and modelling techniques. For both approaches, there are various challenges to be considered.

2.1 Impulse responses

The way a space reacts to signals can be measured by recording its response to a short noise signal, or its response to a sine sweep over all frequencies. This so-called impulse response can be used for reverberation by convolving it with a target signal. Convolution, in the time domain a very computionally expensive process, can be performed in real-time by short-term Fourier transforms. This technique underlies reverberation software such as the SpaceDesigner in LogicPro, the IR plug-ins by Waves, or Altiverb by Audio Ease, to just name a few.

Even though the quality of convolution reverberation is excellent, there are only limited options to influence the reverberation other than choosing a different impulse response. If, for instance, a user selects an impulse response from a forest, then from a city scape, and then decides that the desired reverberation should lie somewhere in between, the impulse responses cannot be interpolated in a meaningful way. The only option is to browse through and try all impulse responses that might apply.

Techniques of artificial reverberation that do not sample, but model acoustic spaces provide more options to influence the reverberation by modifying the model, but they also have some shortcomings, as will be discussed below.

2.2 Modelling

The most realistic reverberation through modelling can be achieved by creating a virtual representation of the space, and simulating the reflection of sound from surfaces. Image source and raytracing methods have been applied successfully to this end. However, these algorithms require careful weighting between model complexity and computation cost. Moreover, outdoor spaces are hard to simulate, since it is hard to ascertain whether irregular objects at large distances still contribute to the reverberation, while the virtual space needs to be bounded at some point. Most importantly, however, the parameters that can be varied in the virtual spaces, such as absorption of the surface, or the size and dimensions of surface elements, are not correlated with perceptual parameters, so it is difficult to create a specific reverberation.

Other, statistical modelling techniques imitate reverberation through delay lines. In principle, this can lead to realistic reverberation. Especially when the diffuse tail end of reverberation is concerned, a dense exponentially decaying series of delays can be a good approximation. Common design elements such as feedback delay lines have a similar effect on the spectrum as interference through wall reflection: parts of the spectrum may show frequency dips due to phase cancellation. Other acoustic effects, such as audible echoes, can also be modelled through long delay times, but are very hard to combine realistically with shorter delay times to a natural sounding reverberation. In short, the

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choice of filter coefficients remains ”half an art and half a science” [9].

The most significant problem of delay line modelling is that the parameters of filter networks — delay time and delay gain — are not perceptual parameters. The delay time is often referred to as ”room size” in the controls of reverberation tools. Yet even this is related more to a visual than an acoustic spatial impression.

As has been seen in both the impulse response and modelling approaches to artificial reverberation, a concept of how humans perceive and categorize acoustic spaces, according to which impulse responses could be organized, or parameters of artificial reverberation could be tuned, is missing. This missing link of the human perception of reverberation can only be bridged by psychoacoustic research.

3. PSYCHOACOUSTIC RESEARCH

Much psychoacoustic research on reverberation has been done since the 1960s. Beranek [2] established some categories for describing concert hall acoustics, such as intimacy, distortion, tonal balance, spaciousness, ensemble, reverberation, or the ratio of early reflections to the reverberant sound field. He rated a number of North American concert halls on the basis of these categories. After a factor analysis of the ratings and comparison with the recorded soundfields he found the time interval between the direct sound and the first reflection, which he calls initial time delay gap, to be the most significant factor. However, since these results are based on his individual judgement, the globality of his findings is unclear.

Gottlob and Siebrasse [7] used impulse response recordings with an artificial head in various European concert halls, which they presented pairwise to a number of participants and asked them to state their preference. A factor analysis of the responses led to four factors which were found to be related to reverberation time, definition, interaural correlation, and the ratio of early lateral to total early energy.

Wilkens and Lehmann [6] used a similar experimental setup, but asked participants to rate the concert space acoustics on scales of antonym pairs. The results were subjected to a factor analysis, the resulting three factors of which were found to be related to strength of sound, centre of gravity time, and the slope of the early decay time of different frequency bands.

Next to research on existing spaces, which is strikingly limited to concert halls, there is also some interesting investigations using synthesized spaces and reflections. Berkley [3] simulated spaces using image source algorithms, varying the reverberation time and source-receiver distance. He reverberated speech signals this way, and presented them pairwise to a number of participants, asking for difference judgements. Multidimensional scaling yielded a two-dimensional representation of the perceived differences, the axes of which he found related to reverberation time and spectral deviation, a measure for the roughness of the frequency response of the room.

Ando [1] synthesized sound fields with an array of speakers. He investigated which artificial reflection patterns would lead to specific acoustic impressions. He found that the most important parameters for reverberation perception are strength, the delay time of early reflections, the subsequent reverberation time, and the inter-aural cross correlation.

The existing research on the perception of reverberation grants a lot of essential insights, however, often the aim consists in finding design parameters for ”good” acoustics supporting speech and music performances, and excluding therefore reverberances which show timbral or temporal irregularities, or perceptible echoes. With this focus on only a limited set of acoustic properties of spaces, the more general question as to how humans perceive acoustic spaces and cognitively organize them, cannot be answered.

4. PSYCHOACOUSTIC EXPERIMENT ON INDOOR AND OUTDOOR SPACES

A psychoacoustic experiment designed by the author [5] therefore included indoor and outdoor spaces, which showed colouration and echoes. Moreover, it was decided that a nonverbal way of judging reverberation was preferable over semantic approaches, since the phenomenon of reverberation can only be captured in language to a limited extent.

4.1 Experimental setup

Impulse responses from four indoor and five outdoor spaces were recorded. The impulse was generated by a starter gun and the impulse responses were recorded with an omnidirectional microphone. The resulting impulse responses were normalized and combined to pairs, which allowed for a comparison of every individual impulse response with every other sound. The resulting 36 pairs were presented to a total of 49 participants, who were listening to the sounds via a high fidelity sound system, in groups of nine to sixteen participants at the same time. The participants were instructed to rate the similarity of the sounds in each pair, on a 16-point scale ranging from similar to dissimilar.

4.2 Results

The multidimensional scaling analysis (ALSCAL) of the occurring judgements could be represented very well in a two-dimensional map (see Figure 1), which explained 98.2% of the variation, with Kruskal’s stress value at s=0.06.

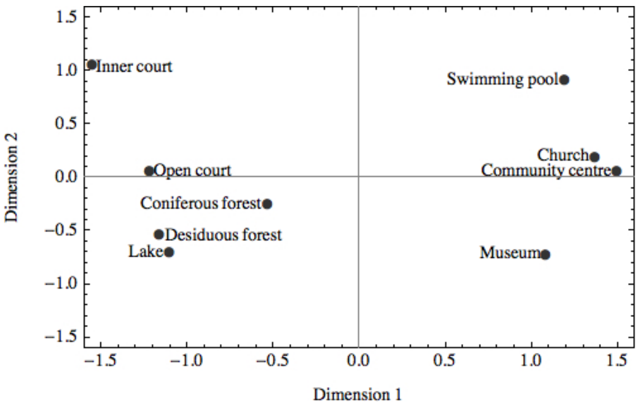

Figure 1: The two-dimensional map representing perceived differences of impulse responses

The two dimensions have been interpreted as the early energy decay, a good measure for which is Early Decay Time (EDT), which specifically considers the energy leak from 0 to -10 dB. This time interval is very short in outdoor spaces, while the audible reverberation can be surprisingly long. Dimension 1 and Early Decay Time are highly correlated (R=0.94). Dimension 2 was found to be related to timbral effects. The integrated autocorrelogram was found to be the closest indication of such spectral periodicities, but only shows medium correlation (R=0.52) with dimension 2.

4.3 Discussion

The present research shows that the Reverberation Time (measuring the decay of energy from 0 to -60 dB), which has been considered as the most prominent aspect in many psychoacoustic studies on reverberation, may actually be much weaker at describing the human perception of acoustic spaces than previously assumed. Indoors, the decay of energy is exponential, which means that Early Decay Time and Reverberation Time are correlated. Outdoors, however, the initial energy leaks much more quickly, which is followed by a exponential tail. The overall time in which the reverberation is audible seems to be much less important than the first drop of energy, however.

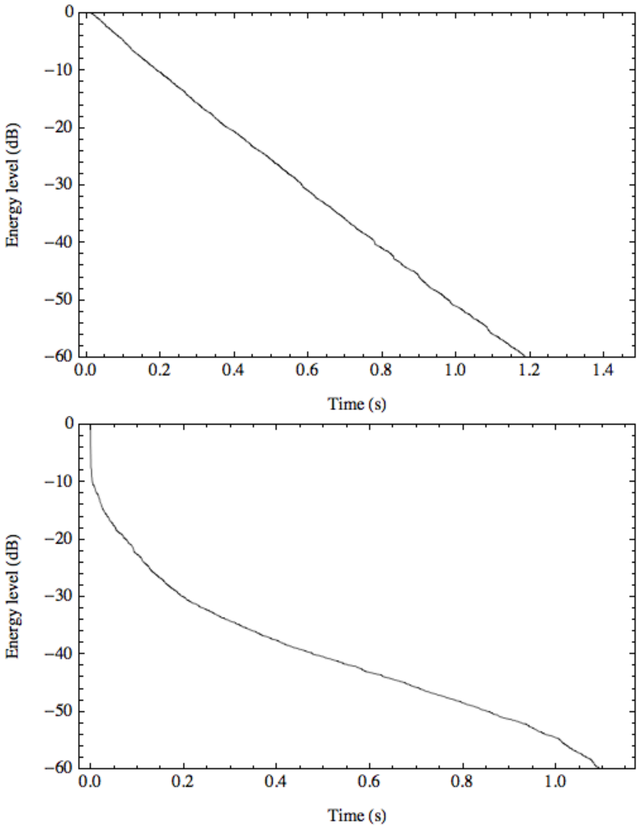

Figure 2: The decay of energy in an indoor and an outdoor space, respectively.

The timbral aspect of reverberation is still hard to assess computationally. Colouration and roughness due to interference effects are perceptually obvious, but are very hard to capture in a measure [8].

One aspect which was neglected in this study was the binaural effect of reverberation. This focus on monaural effects of reverberation means that perceptions of spaciousness or source width cannot be judged on the basis of the data. The binaural effects are certainly important to address in future research, but had to be excluded in this study due to technical reasons.

5. DESIGNING A REVERBERATION INSTRUMENT

As far as reverberation as an audio effect is concerned, it is desirable to have a reverberation model that supports an instrument or voice recording by sustaining energy, and which does not affect the timbre in an unpleasant way.[4]

Re-envisioning reverberation as a musical parameter, however, means that all spaces available to human experience should be accessible: music or sound can travel through various spatial contexts, from a forest, to a basement, to a church. The first step towards this ideal is the implementation of the perceptual map shown in Figure 1 as a parameter space, through which the user can navigate.

Between the techniques of artificial reverberation based on impulse response convolution or modelling, the modelling approach was chosen, since it allows for more flexibility. An improvement on the current delay line modelling techniques is attempted on the basis of the psychoacoustic data.

The energy leak that was found to dominate the perception of reverberating spaces was chosen to be modelled by a leaky integrator:

$$y_t = -Ay_{(t-1)} + x_t$$

The leak coefficient A can be used to vary between a quick drop, or a sustain of energy, and hence model the initial decay development in inside and outside spaces.

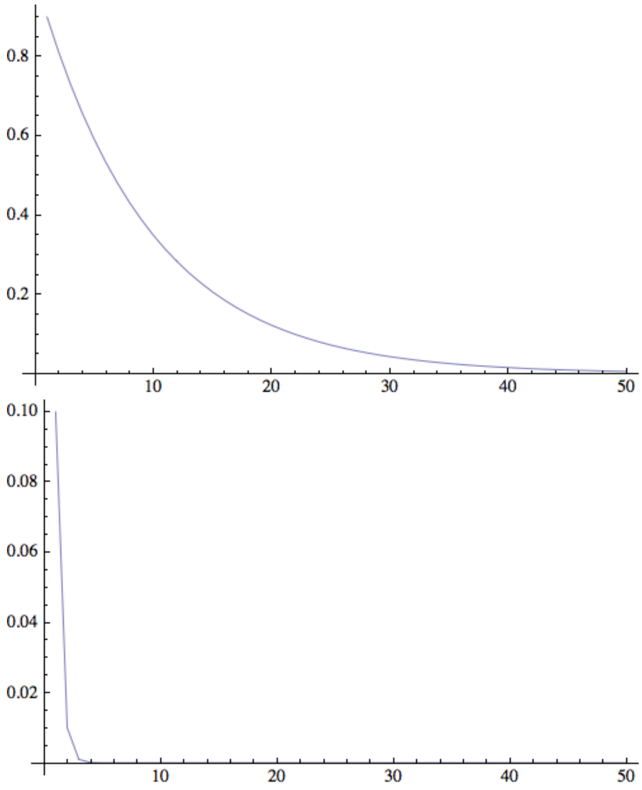

Figure 3: An impulse fed into a leaky integrator with the leak coefficients of 0.9 and 0.1, respectively.

The dimension of timbre is modelled through a set of eight parallel comb filters. The delay time of each comb filter feedback loop can coincide with another, which will lead to a severely coloured spectrum, or the frequency dips of the different filters can be shifted in respect to each other so as to achieve a less coloured signal.

Close attention has to be paid to the filter coefficients, however: it is very difficult to choose them so that the colouration is still perceived as an effect of reverberation. Therefore, the open source Freeverb algorithm[1] was taken as a source for well-tuned filter coefficients.

Through an ensuing series of allpass filters a realistic length of the overall reverberation is ensured. Figure 4 gives a rough overview of the signal chain implemented in the re-

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[1] `http://freeverb3.sourceforge.net/`

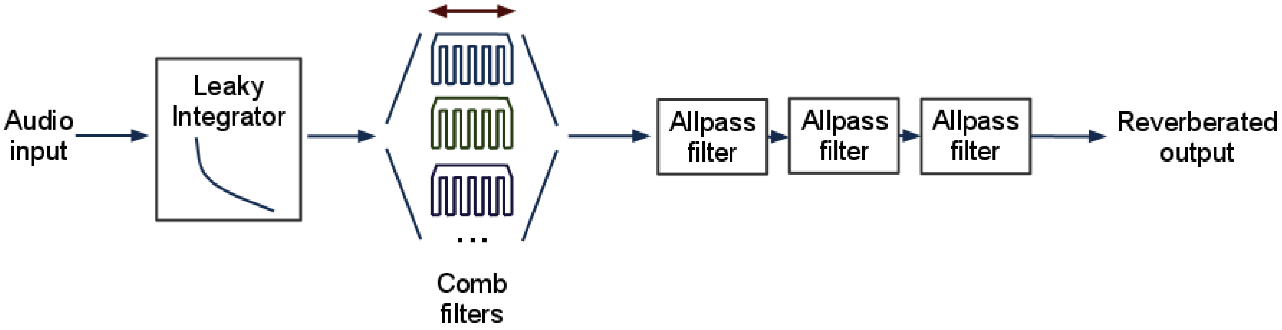

Figure 4: Signal chain of the reverberation instrument.

verberation instrument. The adjustable parameters are the leak coefficient of the leaky integrator, and the shifting of the comb filters, here sketched as combs with prongs representing frequency dips.

While this design rests on existing reverberation algorithms, the control of parameters along the two dimensions of the perceptual map should be a significant improvement to allow intuitive control of reverberation. The reverberation instrument as described here has been realized in SuperCollider and can be controlled with a Wii Motion Plus controller. Other interfaces, for example HID devices or camera tracking systems, are conceivable and can be unproblematically connected via Open Sound Control.

6. CONCLUSION

Controlling reverberation as an instrument is a dream which can only be obtained by understanding how humans perceive and cognitively organize reverberation. It has been shown that current techniques to obtain artificial reverberation do not fulfill this dream, mainly because the physical parameters controlling modelling, or describing an impulse response, are not linked to our perception. Psychoacoustic research can provide this bridge between the physical and perceptual realm, but has sadly mostly been restricted to indoor spaces. The study presented in this paper overcomes this limitation, and provides results which make an instrumental navigation through acoustic spaces more achievable. One important aspect of reverberation, namely binaural effects, have not been considered so far, however. More extended psychoacoustic research is needed, therefore, and its results should be integrated into the model presented here.

7. REFERENCES

[1] Y. Ando. *Architectural acoustics: blending sound sources, sound fields, and listeners.* Springer, 1998.

[2] L. L. Beranek. Concert hall acoustics – 1992. *Journal of the Acoustical Society of America*, 92(1):1–40, 1992.

[3] D. Berkley. Normal listeners in typical rooms. In G. Studebaker and I. Hochberg, editors, *Acoustical Factors Affecting Hearing Aid Performance*, pages 3–24. University Park Press, 1980.

[4] B. Blesser. An interdisciplinary synthesis of reverberation viewpoints. *Journal of the Audio Engineering Society*, 49(10):867–903, 2001.

[5] B. Janssen. Cognitive representation of reverberating rooms and spaces. Master's thesis, Hamburg University, 2008.

[6] P. Lehmann and H. Wilkens. Zusammenhang subjektiver beurteilungen von konzertsälen mit raumakustischen kriterien. *Acustica*, 45:256–268, 1980.

[7] D. G. M. R. Schroeder and K. Siebrasse. Comparative study of european concert halls: correlation of subjective preference with geometric and acoustic parameters. *Journal of the Acoustical Society of America*, 56:1195–1201, 1974.

[8] A. M. Salomons. *Coloration and Binaural Decoloration of Sound due to Reflections.* PhD thesis, Technical University Delft, 1995.

[9] U. Zölzer. *DAFX - Digital Audio Effects.* Wiley, 2002.