The Well-Tempered Reverberator: an Instrument for Composing Rooms Intuitively

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ABSTRACT
The modelling of room acoustics can be performed with a number of different approaches, all of which entail some advantages as well as disadvantages, which mostly leads to a trade-off between acoustic realism and computing time. An algorithm that allows for dynamic change between spaces must therefore combine different techniques to optimize the quality of representation as well as performance. Such an optimization must be powered by insights into the human perception of reverberation. Psychoacoustic research exists, but is mostly limited to inside spaces, or even only concert halls, and is therefore not representative of all possible acoustic spaces. An experimental design in which inside and outside spaces were investigated is presented. Paired impulse responses from these spaces were rated by listeners on a difference scale. A multidimensional scaling analysis of the data points to the early energy decay as the most decisive feature in distinguishing spaces from each other. Similar experiments should follow, which can help to develop a comprehensive theory of reverberating spaces. Not only the implementation of findings from such experiments, but also the development of an intuitive user interface is required to perfect the reverberation instrument.

Keywords
Psychoacoustics; Room Acoustics

1. INTRODUCTION
Reverberation is a vital element of human communication: be it speech, or be it music. The acoustic conditions of performance spaces – indoors and outdoors – have influenced musical composition for centuries. Ever since digital technology allows for the recreation of virtually any room, it is conceivable that the acoustic space itself can be employed as a compositional parameter. Most reverberation tools today either employ statistical, fast methods, even though they cannot model some acoustic phenomena, or they "sample" a real or virtual space in the form of impulse responses. To reverberate a signal with an impulse response, it must be convolved, which has the disadvantage of being less fast and versatile than the statistical methods.

A reverberation instrument must allow for dynamic manipulation of reverberance, but also enable users to locate their sounds in any acoustic space; hence, a trade-off between both methods must be achieved. To achieve a good compromise, it is indispensable to determine which aspects of the temporal and spectral fine-structure of a reverberance can be perceived, and which cannot be perceived by the human auditory system. Only in this way can data be effectively reduced, without a loss in perceptual quality. Most psychoacoustic research of the past decades, however, has been devoted to improving concert hall acoustics. The question as to what makes acoustics "good" has dominated, rather than an unbiased desire to understand the way humans perceive and categorize all kinds of different acoustic spaces.

Different ways to close this gap of knowledge need to be followed, one of which is the investigation of impulse responses through multidimensional scaling. The advantage of this method is its use of difference judgements, which have more inter-subjective reliability than judgements requiring a rating according to verbal descriptions.

The dimensions in which acoustic spaces are categorized can then be linked to objective measurements of room acoustics, and finally be implemented in a reverberation software. In order for this software to become a usable reverberation instrument, however, the objective parameters need to be linked to a meaningful user interface.

An overview of different approaches to artificial reverberation is given first, then the psychoacoustic findings on reverberation are considered. An experiment by the author is presented, which however is only the first step towards the free musical control of reverberation.

2. ARTIFICIAL REVERBERATORS
In principle, reverberation can be seen as a series of repetitions of the original signal, which have a different amplitude. In order to reproduce this phenomenon, two approaches are possible: the

impulse response approach, which strives to reproduce the temporal and spectral structure of a real space's reverberance; and the stochastic approach, which assumes that the density and intensity of reflections in real spaces can be convincingly reconstructed using probabilistic methods.

The methods based on impulse responses include either the measurement of a real room or space, or the calculation of the impulse response for a virtual space. The impulse response can then be convolved with a target signal to reverberate it, generally leading to very convincing results. However, both the obtaining of an impulse response and the ensuing convolution have their problems and limitations, as will be discussed below.

The stochastic approach mainly relies on delay lines, which can replicate room reflections as repetitions of a signal at a fixed delay time and gain. A single delay line will not sound convincing, so different combinations of delay lines are in use. These techniques can provide very fast computation speeds, but do not always produce convincing results. It is of course conceivable that the complexity of a delay line network increases to the extent that its impulse response corresponds to the impulse response of a real room, hence the two approaches are ultimately connected.

2.1 Problems of the Impulse Response Approach

A space's impulse response is the series of reflections with which it reacts to a sound emission. This can be considered both in the time and in the frequency domain, as either the arrival time and intensity of reflections, or as a space's characteristic boost of some, and attenuation of other frequencies. Theoretically, the measurement of impulse responses requires an impulse of infinitesimal length and infinite energy. Such a signal does not exist, but can be approximated by a crack from a spark or a starter gun. Alternatively, the response of the room can be measured in the frequency domain, by using a so-called sine sweep: an oscillator stepping through all frequencies. But this approach, too, has its limitations, as the reproducing loud speakers will not respond to all frequencies in the same way. Distortions of the impulse response must therefore be accepted if they are measured in a real space, but the deviations from the "ideal" response are not too severe.

Some of these distortions can be avoided in a digital model of a space. However, the computation of the impulse response suffers from other problems, as the spreading, scattering and attenuation of sound needs to be modelled. Moreover, effects such as diffraction of longer wave forms around edges and obstacles complicate the modelling. Most algorithms generating impulse responses from a virtual space make use of geometric methods, such as the image source method. In this approach, the wavefronts are constructed as rays, and walls and obstacles are treated as acoustic mirrors. With increasing order of reflections, however, the number of possible paths increases exponentially, leading to very long computation times. Other virtual methods to measure impulse responses, such as ray tracing, finite element or finite boundary methods, suffer likewise from potentially high computational expenses.

After the impulse response of a space has been determined by any of the above-mentioned methods, another problem ensues: the convolution of a target signal with the impulse response requires a large number of multiplication and addition operations, which cannot be performed in real time. The computation can be accelerated by transforming both the target signal and the impulse response to the frequency domain; a multiplication in the frequency domain is equivalent to a convolution in the time domain. Hence, fast fourier transforms permit the reverberation of a signal in time windows, which can be played back while the next segment is reverberated. However, the interpolation between such windows remains a problem. Moreover, the options to manipulate an impulse response are limited: no dynamic transition from one reverberance to another is possible.

2.2 Problems of the Stochastic Approach

Room reflections can also be implemented as a series of delays. Assuming an exponential decay of energy, a feedback delay line with a gain smaller than unity can reproduce a room's energetic behaviour in response to a signal. However, more complexity is needed to achieve a convincing reverberator. The most well-known filter network consisting of different feedforward and feedback delay lines is the Schroeder reverberator sometimes called Freeverb, which combines a number of parallel comb filters, which generate spectral density, with a series of allpass filters, which generate temporal density. [9] However, the choice of parameters – delay time and gain – remains largely "half an art and half a science." [12]

The control of filter networks is not limited to the combination of simple delay lines. New approaches include tapped delay lines, i.e. delay lines with multiple outputs, or multiple input, multiple output (MIMO) networks, which connect the inputs and outputs via matrix transfer functions. [10] Waveguides, two-dimensional delay lines often used for modelling travelling waves along strings or pipes, can also be employed to model paths of travelling waves in a room. Yet the advantage of the stochastic approaches – their fast computation time and realtime applicability – decreases with every increase of complexity.

A good, realistic reverberance is no doubt achievable at real time speed with filter networks. Especially the tail end of an exponential decay can be modelled sufficiently well, whereas many algorithms calculate the first reflections by means of an image source algorithm. However, what about non-exponential decays, colouration or flutter echoes? Rooms and spaces often show such behaviour (see **Fig.1**), but reverberators operating on delay line principles do not. It may be true that we do not need such reverberances if we want to master a vocal or instrumental recording. [4] Yet even if spaces are acoustically "bad", in that they distort the signal to an unclear, unintelligible result, they are part of the range of human experience, and can very well have more than interesting applications for non-instrumental music such as the electro-acoustic genre.

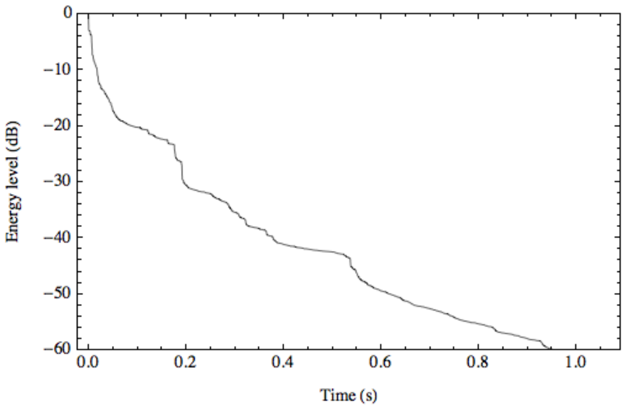

Figure 1. Example for a non-exponential decay as found in an open courtyard: statistical methods are difficult to apply.

2.3 Hybrid Methods

A reverberation instrument needs to provide a control of all possible spaces: the unique acoustic features of concert halls, bathrooms, forests, courtyards, streets and any other imaginable reverberance. On the other hand, the control of these spaces should not be only a matter of opening an impulse response from a library: realtime manipulation and dynamic transition between spaces is needed. From the problems pointed out above, it is evident that it is not sufficient to limit oneself to one of the outlined approaches: only through a clever combination of different implementation methods can a convincing, versatile and dynamic reverberator be achieved. The choice of methods must then be guided by the way humans perceive reverberation: which aspects of reverberation are those that enable us to distinguish and categorize spaces, which aspects of reverberation can be implemented at reduced resolution, since they are mostly inaudible? Psychoacoustic findings are needed to answer these questions.

3. PSYCHOACOUSTIC RESEARCH ON REVERBERATION

Investigations on the perception of reverberation have been conducted since the 1960s. Most of the early studies focussed on concert halls, which were either rated during a concert, or in listening experiments with recordings. The subjective responses were then related to objective differences of the reverberances.

Later research also employed artificial reflections, such as impulse responses generated by image source algorithms, or early reflections of a synthesized sound field. In this way, the stimuli can be controlled in a much more sophisticated way, and the listeners' responses can be related to objective measures more precisely.

3.1 Early Studies on Concert Halls

One of the first to investigate the perception of reverberation, Leo Beranek established a number of categories which he found to be important in the quality judgements for concert halls. He rated a number of different concert halls based on these semantic descriptions during orchestral performances, and subjected the ratings to a factor analysis. This showed that the quality judgements were most prominently linked to the length of the time interval between direct sound and the first reflections. [2] It has been criticized, however, that his results are merely based on his own judgements, which makes their global validity doubtful. Yet his semantic categories are still an important achievement, showing the width of sensations attached to reverberation.

Other researchers took an approach comparable to Beranek's, such as Hawkes and Douglas [6], or Wilkens and Lehmann. [8] The advantage of such a method is the weighting provided by the factor analysis: this highlights the most important semantic categories and facilitates the interpretation of the results. On the other hand, these studies suffer from the fact that acoustic experiences are very hard to verbalize: even though subjects may perceive reverberation in similar ways, they may diverge considerably in their word choices to describe differences, yielding very non-uniform data.

In 1974, Gottlob and Siebrasse [11] chose a different approach, asking for preference judgements between two impulse responses from different concert halls. This eliminates the problem of semantic ambiguity, and a factor analysis can be performed on the data. The resulting four factors were found to be correlated with the objective measures reverberation time *T*, definition *D*, interaural cross-correlation *IACC*, and the ratio of early lateral to total early energy.

The findings of these and other studies on concert halls are very valuable to gain an insight into the many parameters that govern the perception of reverberation. However, it is doubtful whether these parameters are also the most salient features of spaces other than concert halls, such as small rooms with prominent resonances, or outside spaces. Hence, studies focussing on more generic spaces constitute another step forward towards a comprehensive understanding of reverberation.

3.2 Studies on Artificial Reverberation

In a relatively unknown experiment, Berkley [3] investigated speech stimuli derived from an image source algorithm. He used a rectangular virtual room, of which the room size was kept constant, while the reverberation time (i.e. absorption of the walls) and source-receiver distance was varied. He collected difference judgements on paired impulse responses in a listening test, which were subjected to a multidimensional scaling algorithm. This yielded a two-dimensional map, of which one dimension was related to the reverberation time, the other to the timbral development of the reverberance.

In the 1980s, Ando [1] was able to investigate room reflections in even more detail: using wave field synthesis, he had control over the delay and energy of single reflections. He played a piece of orchestral music with different settings for the strength and delay of early reflections to the participants of his experiments. The responses yielded a series of orthogonal factors of subjective preferences, among which the reverberation time, the sound pressure level *SPL* and the interaural cross-correlation were found to be most prominent.

3.3 Applicability of Results to the Proposed Reverberation Instrument

As these studies exemplify, most of the psychoacoustic research on reverberation is limited to inside spaces, if not even focussed on concert halls. The results of these studies cannot be employed to understand the cognitive representation of outside spaces, or other spaces showing a significantly different reverberant behaviour. Since human experience is not limited to rectangular rooms or concert halls, it is important to understand how all kinds of spaces are handled by the human auditory system. Only then a comprehensive theory on human categorization of reverberation can be achieved.

Moreover, many studies employ an assessment of the reverberation quality, i.e. they assume that there is "good" and "bad" reverberation. In terms of a reverberation instrument, however, such a distinction is not applicable, since any space can be of musical interest, and should be within the range of the instrument. Hence, the question should be more directed at the overall differences of spaces: how do humans distinguish and cognitively navigate through their acoustic environment?

4. COGNITIVE REPRESENTATION OF REVERBERATING SPACES

An experiment was performed in order to overcome some of the limitations to earlier studies, and to arrive at a more complete picture of human perception and cognitive representation of reverberation.

Impulse responses from inside and outside spaces were presented to listeners in pairs, which were asked to give difference judgements. A multidimensional scaling analysis was performed. These methodological choices are shortly discussed.

The result is a two-dimensional map representing the perceived differences with satisfactory accuracy, of which one dimension could be clearly correlated to the early decay time, whereas the second dimension was more difficult to interpret, as will be discussed below.

4.1 Experimental Design

A number of impulse responses was recorded in inside and outside spaces, using a starter gun as an impulse. Two small-diaphragm condenser microphones (*Studio Projects C4*) with omnidirectional capsules were used for recording, and the data was transferred to a notebook running the sequencer software *Audacity* via a *RME Fireface 200*. The resulting impulse responses were normalized, the direct sound was removed, and nine reverberances were selected: five stemming from outside, four from inside spaces.

The impulse responses were then combined to a total of 36 pairs, allowing for an inter-comparison of all stimuli. These pairs were then presented in mono (the secondary microphone having pre-eminently measurement purposes) via speakers to a total of 49 participants, all of which were Musicology students and lecturers at the University of Hamburg. They were asked to rate the pairs on a sale ranging from "very similar" to "very dissimilar".

The responses were then averaged and subjected to the multidimensional scaling routine ALSCAL, as implemented in SPSS.

4.2 Methodology

Difference judgements are a good instrument to access the cognitive parameters by which complex phenomena are categorized. They do not necessitate long training sessions of the participants, or the limitation to "expert" listeners for the performance of listening experiments. Reverberation is a phenomenon that every non-hearing-impaired human being is familiar with, even if not everyone would be able to express the perceptional changes caused by a change of reverberation in accurate room acoustic terms.

Difference judgements have been successfully employed by Grey in his 1977 study on timbre, the perception and categorization of which is also complex, and hard to analyze semantically. [5] He presented his participants with stimuli of re-synthesized instrument timbres at a fixed pitch, in which the initial transient was missing so as to focus on the steady-state timbre.

While difference judgements could doubtlessly also be performed on the basis of more meaningful stimuli, such as music or speech, the present experiment also limits itself to the comparison of rather abstract sounds, namely impulse responses. This is meant to assure that other cognitive processes, such as melody or speech recognition, do not interfere with the difference rating. Moreover, certain sound sources may seem more natural in some reverberances than in others, and lead to further distortions.

Difference judgements are collected in order to perform a multidimensional scaling analysis. This process fits the perceived difference to an n-dimensional map ordering the stimuli according to distances. With increasing dimensions, the fitting of data becomes more feasible, but the interpretation of the map is more difficult.

There are different multidimensional scaling routines which iteratively minimize the difference between the perceived and the mapped distances. The success of the mapping can be expressed in different indexes, as for instance Kruskal's stress factor, with 0 as the optimal fit. [7]

4.3 Results

98.2% of the variation in the participants' responses could be explained by a two-dimensional map, with Kruskal's stress value at s = 0.06, as can be seen below:

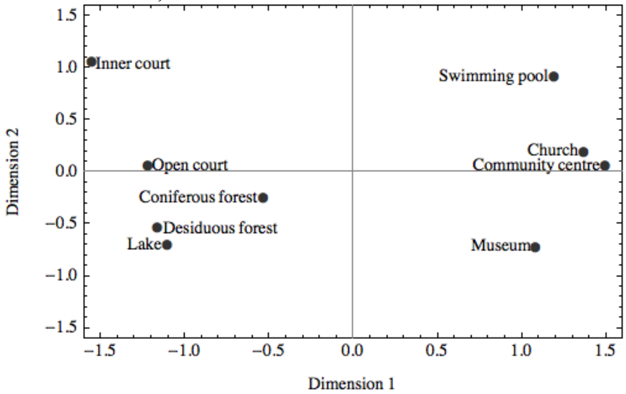

Figure 2. MDS results of a listening experiment on impulse responses

4.4 Discussion

Dimension 1 of the shown representation was found to be highly correlated (R=0.94) with the early decay time of the impulse responses. This seems not to be surprising at first sight, since various other studies have established the importance of the reverberation time, and early decay time and reverberation time are closely related. The early decay time considers the first drop by -10 dB of the energy, whereas the reverberation time generally focusses on the drop from -15 to -35 dB. For exponential decays, these measures will allow to estimate the point in time at which the reverberance drops below the hearing threshold at -60 dB. However, for non-exponential decays, as may be found in many rooms or outside spaces, the measured reverberation time or early decay time is very short, whereas the actual reverberance can be of a duration comparable to inside spaces. Everyone who shouted or clapped their hands in a forest can picture this long, but very subdued reverberance.

From the current data it is evident that it may be not the total length of the reverberation at all which is important for the categorization of reverberation, and that it is mainly the early decay, which is steady for closed rooms, but mostly rapid for outside spaces, which is one of the main cues according to which spaces are distinguished. The importance of this result for the synthesis of artificial reverberation still needs to be verified.

Dimension 2 was more difficult to analyze: it correlates weakly (R=0.52) with the integrated autocorrelogram of the impulse response, a measure of periodicities. Periodicities can lead to a filtering of the spectrum due to interferences. This yields the assumption that Dimension 2 is related to a timbral component, detecting spectral or temporal variations. However, no convincing measure for such effects has been established for reverberation so far, therefore audible timbral effects cannot necessarily be measured.

4.5 Outlook

Due to the limited number of stimuli used in this experiment, the full picture of reverberation needs to be investigated in a range of similar experiments. Moreover, since technical restrictions did not allow for binaural recordings, the influence of sound incidence cannot be assessed from the present data. Future research will remedy these shortcomings.

5. FIRST STEPS INTO AN ACOUSTIC LANDSCAPE

The way to an easily controllable reverberation instrument has just begun: the hypotheses extracted from multidimensional scaling experiments need to be tested in a more systematic way. Third-party software may be employed for this, but also the first versions of the reverberation instrument itself.

Moreover, the effect of reverberation on meaningful sonic objects needs to be investigated: does the shaping through a reverberance have a different impact on a speech signal than on traffic noise, for instance? Do experiences with typical spaces in which we expect to find specific sound sources play a role in our evaluation of reverberance?

The relationship between sounds and acoustic spaces needs to be understood in order to grasp the musical material opened up by a sophisticated control of reverberation. Only then a meaningful interface can be designed, which will allow composers, musicians and other users to control reverberation intuitively as a musical instrument.

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