Early decay development in inside and outside reverberating spaces

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1. Introduction

Reverberation is a basic though often unconscious form of spatial experience. It is of importance in everyday contexts, but also for musical composition, for the post-production of films, or for various kinds of auditory virtual environments. The question remains how humans distinguish between different reverberant spaces. Approaches towards this problem were often limited to investigating inside rooms only. To approach a more comprehensive understanding of the phenomeon of reverberation, impulse responses from both inside and outside spaces were recorded to be used in a listening experiment. The difference judgements of the participants were evaluated using multi-dimensional scaling. The results show that it is especially the early decay development that is used as a cue to distinguish spaces.

2. Related works

The question as to the psychoacoustic evaluation of room reflections has sparked off interesting research projects for decades. For instance, Gottlob and Siebrasse [1] asked participants to rate binaural stimuli recorded in concert halls in the form of preference judgements. The performed factor analysis yielded four factors, which were found to be related to the objective measures reverberation time *T*, definition *D*, interaural cross-correlation *IACC*, and the ratio of early lateral to total early energy.

Berkley [2] investigated stimuli derived from a room simulated by an image source algorithm. He did not vary the room size, however, but was mainly interested in the effect of different reverberation times and source-receiver distances. The difference judgements of a listening test were subjected to a multidimensional scaling routine, which yielded a two-dimensional cognitve space, of which one dimension was related to the reverberation time, the other to the timbral development of the reverberance.

Ando [3] established a series of orthogonal factors of subjective preferences derived from studies with synthesized sound fields, among which the reverberation time, the sound pressure level *SPL* and the interaural cross-correlation were found to be most prominent.

As these studies exemplify, most of the psychacoustic 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, since outside spaces show a significantly different reverberant behaviour. Since outside spaces are vital to everyday human experience, it is important to understand how different outside spaces are distinguished by the human hearing, and how they relate to inside spaces. Only then a comprehensive theory on human categorization of reverberation can be achieved.

3. Experimental setup

For a listening experiment comparing different impulse responses, a control of the physical parameters governing the stimuli would be highly desirable. Yet physical models as in raytracing or image-source algorithms are not currently able to acoustically reproduce outside spaces.

Therefore, different impulse responses were recorded in inside and outside spaces. The impulses were generated with a starter gun and recorded with omnidirectional microphones. The impulse responses yielding the stimuli of the listening experiment stemmed from a community centre, a church, an indoor swimming pool, a museum, an inner courtyard, an open courtyard, a coniferous and a desiduous forest, and a lake.

The impulse responses were normalized and randomly paired, yielding 36 pairs. 49 participants were asked to rate the difference between each pair, on a scale ranging in 16 steps from "very different" to "very similar". The difference judgements were then analyzed using multidimensional scaling.

4. Results

The obtained difference judgements can be represented satisfactorily in two dimensions, as shown in Figure 1. The inside and outside spaces are clearly separated on the axis of Dimension 1, which explains 96% of the variation, with a stress value of STRESS = 0.1. Dimension 2 improves the mapping only slightly, with STRESS = 0.06, explaining 98% of the variation. Hence, Dimension 2 is somewhat more difficult to interpret.

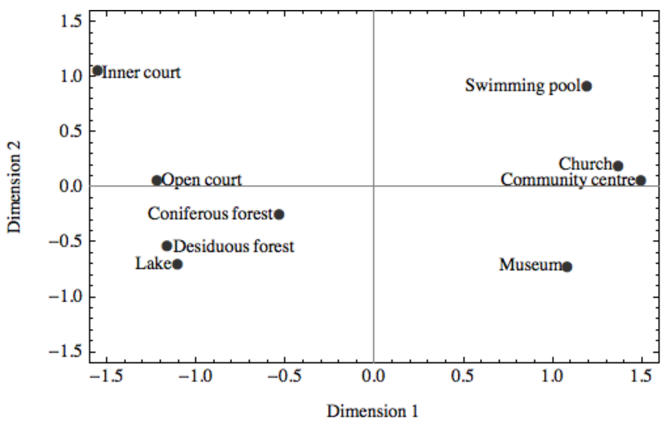

Figure 1. The multidimensional scaling representation of difference judgements comparing nine impulse responses of inside and outside spaces.

5. Discussion

Dimension 1 was found to be significantly ($p < 0.01$) correlated with the objective measure Early Decay Time (*EDT*), at R = 0.94. This has interesting implications for the psychoacoustic distinction of reverberant spaces: *EDT* is determined by the time in which the energy drops from 0 to -10 dB (multiplied by six to receive the -60 dB reduction corresponding to the hearing threshold). This can be a remarkably short time interval in outside spaces, as can be seen in Figure 2.

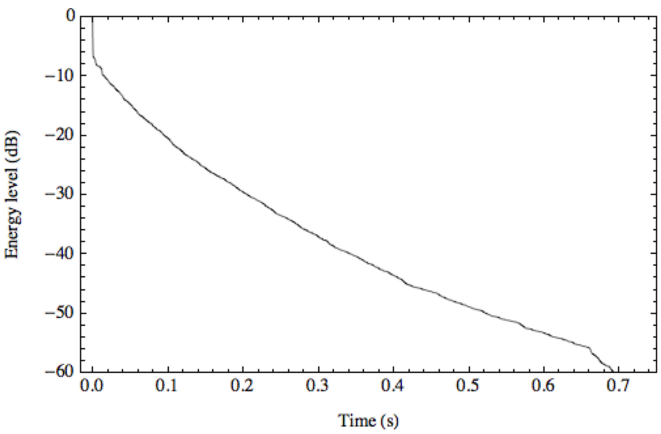

Figure 2. The energy decay as measured in the desiduous forest, exemplary for an outside space. The shown decay curves were determined using the backward integration method as proposed by Schroeder[4].

It is interesting to observe that it is not the length of the total audible reverberance which is taken into account by listeners when they distinguish different spaces. The total reverbeance can be quite long in outside spaces, but is mostly is of an order of one second: it is considerably longer than the *EDT* or Reverberation Time *T* would lead us to expect.

In inside spaces, there is a relation between *EDT* and the total audible reverberance, since the decay development of the early energy can be expected to continue according to an exponential law (see Figure 3). The same holds true for the determination of *T* from the energy drop from -5 to -35 dB.

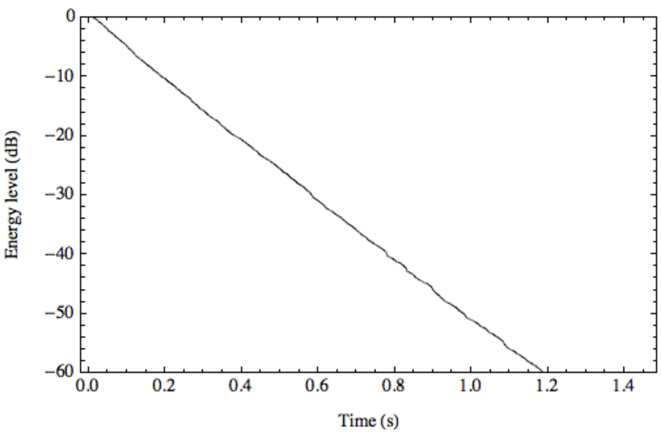

Figure 3. The energy decay as measured in the community center, exemplary for an inside space.

For outside spaces, however, these measures do not give us a clear idea of the length of the audible reverberance: the early decay is rapid, but is followed by a much flatter slope until the reflections drop below the hearing threshold. Different measurement techniques would be needed to obtain a realistic value for the length of audible decay, as for instance suggested by Sakai [5].

Yet it is essential to note that for the psychoacoustic categorization of reverberating spaces, the early decay development seems to be much more important than the length of the total audible decay; it may be this early development which is instrumental in distinguishing different spaces, and psychoacoustically separates inside from outside spaces.

In this respect, it would be interesting to investigate limiting cases: the comparatively smooth decay curve measured by a yard enclosed by walls (Figure 4) shows that there seems to be a transition between the steady inside and the rapid outside early decay, depending on the proximity of reflecting surfaces. If such a transition also exists in the perception space still remains to be verified.

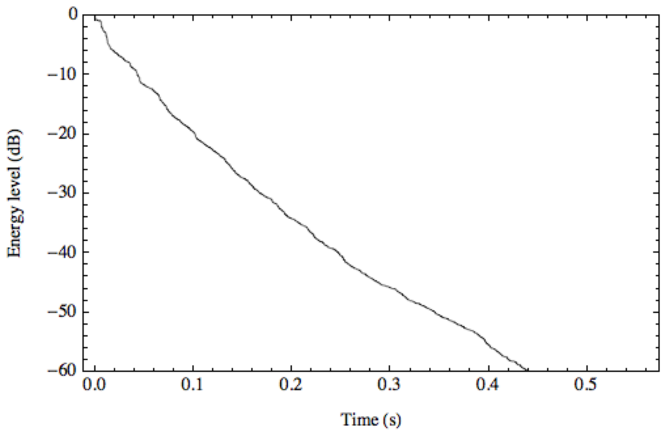

Figure 4. The energy decay as measured in the inner courtyard: relatively steady decay in an outside space.

The second dimension of the perception space is harder to interpret than the first dimension; however, it seems to be related to some timbral component of the reverberances. It shows a medium correlation (R=0.52) to the integral of the autocorrelograms for the respective impulse responses, a measure for colouration as proposed by Kuttruff [6].

One reason why this effect is so weak may be the comparatively small timbral variation in the stimuli. The effect of the early decay seems to outweigh the differences in timbre, which led only to moderate distinctions. A similar experiment using more impulse responses of quite different timbral characteristics might therefore be rewarding.

6. Conclusion

The present experiment shows that the psychoacoustic distinction of different reverberating spaces relies substantially on the early decay development, and not on the total length of the reverberance. Outside spaces show characteristically a steep early decay, which may be the main indicator of an outside space to listeners. A timbral component in the cognitive mapping of spaces seems to be indicated, but cannot be conclusively verified by the current results. Further investigation of sound fields in inside and outside spaces is therfore indispensable to achieve a comprehensive view on the cognitive evaluation of reverberation.

References

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