INVESTIGATION ON THE PERCEPTION OF ANISOTROPIC REVERBERATION

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1 INTRODUCTION

The sound field in a room is a superposition of multiple soundwaves, whose amplitude, phase and direction of propagation vary depending on the room boundaries. The reverberant – or "late" – sound field is often considered as a diffuse field, *i.e*. as a sum of infinity of incoherent plane waves[11]. Although it is commonly assumed that homogeneity – uniform energy distribution within the room – and isotropy – uniform energy distribution over the directions it is observed in – are properties of reverberant sound field, listening environments do present neither of these[1, 15].

In room acoustics, the inhomogeneity of reverberant sound field is well-known; acoustical parameters should always be measured from multiple seats. As an exemple, the seats under the balconies are known to lack listener envelopment. The anisotropy of the late sound field, that is the variations of late energy as a function of direction, is however much less analysed in room acoustics. Yet it has been shown that it is audible[1, 15].

Authors have suggested multiple objective parameters to describe spatial impression, and some of them are dependant from the reverberation direction[3, 8, 14]. Late lateral level LG_{80}^{∞}, which is the objective criterion for listener envelopment (LEV), depends on a cosine weighting of the reverberation direction, with the 0 pointing to the source. Front to Back Ratio (FBR) is the ratio between frontal and rear late reverberation.

These criteria remain rarely measured and analysed by acousticians. Studies from Lachenmayr and Wakuda and *al*. showed that, even though lateral reverberation is the most correlated to envelopment, top and rear late reverberation also contribute to LEV[12, 16]. More recently, Alary and *al*. demonstrated the audibility of anisotropy in listening environments and highlighted the need to take it into account in spatial audio applications[1]. Berzborn and Vörlander initiated an approach to investigate anisotropy of reverberation in performance spaces[2]. Lastly, Kahle argued in a return from experience that excessive reverberation from around and behind the stage has a negative influence on the listeners but also the musicians experience. He suggested that the direction of reverberation has an effect on spaciousness, clarity and distance perception.

As subjective impressions of room acoustics are not yet fully understood nor described by acoustical parameters, the knowledge of the effects of anisotropic reverberation on our auditory perception would lead to improved hall designs. To this end, the approach taken was based on two "paired comparisons" listening tests, in which monaural parameters were constant. Their aim wasn't to establish a correlation between subjective impressions and objective criteria but rather to explore various consequences of directional variations of late reverberation. The purpose of this paper is to raise awareness on these effects and to encourage acousticians to analyse spatial measurements in future projects.

The article is organised as follows : section 2 describes both listening tests, whose results are then presented in section 3. Section 4 concludes. A short appendix on spatial room impulse responses (SRIR) is included.

2 LISTENING TESTS

2.1 Overview

To investigate the effects of various spatial distribution of late energy on auditory perception, two listening tests have been conducted at Kahle Acoustics. The stimuli were room auralisations synthetised in a listening station that was implemented in Max/MSP and based on the Spat~ library developped by IRCAM[4]. The sound was reproduced by headphones with a head tracking device. Thanks to this system, the dynamic binaural synthesis of synthetic environments was plausible enough.

The first listening test compared isotropic reverberation with a configuration without frontal reverberation. In a pre-test, participants had noticed a loss of intelligibility as the frontal late energy increased. Literature has shown that late lateral energy and energy from behind contribute to envelopment, thus the second test was designed to compare the two and to identify any other perceptual differences (clarity, dynamics, timbre, etc).

In this paper, the spatial distribution of the reverberated sound field was parametrised by restricting ourselves to the 6 directions of the axes of the Cartesian reference frame. Directional reverberation could be described with a directional decay time $RT(\text{dir})$ and late energy – or late strength – $G_{70}^{\infty}(\text{dir})$ for each frequency band (see appendix).

2.2 Stimuli

The stimuli were generated so that early reflections and late reverberation were totally independant. Early reflections were defined one by one, each associated with a virtual source. In this article, the direct sound and 11 early reflections were kept constant throughout the tests in order to avoid bias due to possible masking effects.

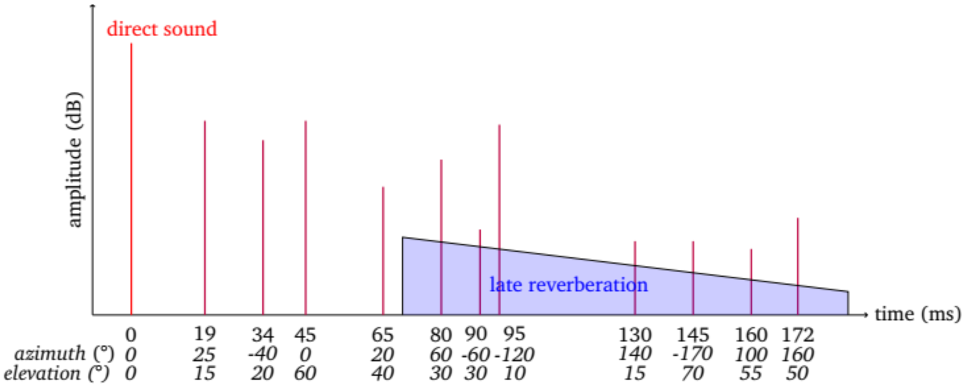

Figure 1: Echogram – early reflections synthetised for the tests.

Late reverberation was generated by 6 FDN-type artificial reverberators (*Feedback Delay Networks*), whose decorrelated outputs were routed to 24 virtual sources, *i.e.* 4 sources per direction (Figure 2). The choice of the number of virtual sources was motivated by Kirsch and *al.*[10]. The onset of the reverberation was set at 70 ms during the listening tests.

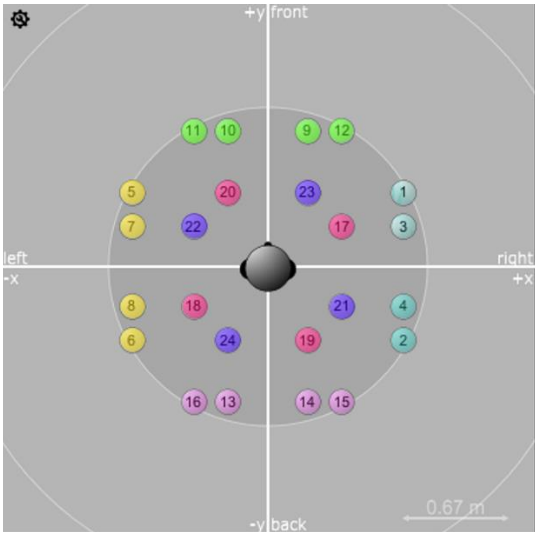

Figure 2: Plan view of the virtual reverberation sources (Spat~) interface.

In order to reduce bias in comparisons, directional energies G_{70}^{∞}(dir) were defined so that the total energy remained equal between compared stimuli. Similarly to Romblom and *al.*[15], increasing energy in a direction was balanced by a decrease of energy for the other directions, and vice versa. The usual monaural parameters were therefore constant during each comparison.

For both listening tests, two configurations with different total reverberated energy and decay time were defined. Their parameters G_{70}^{∞}(dir), RT were –1 dB and 1,7 s for configuration A and 2 dB and 2,3 s for configuration B (medium frequencies values). Figure 3 details these parameters in each frequency band.

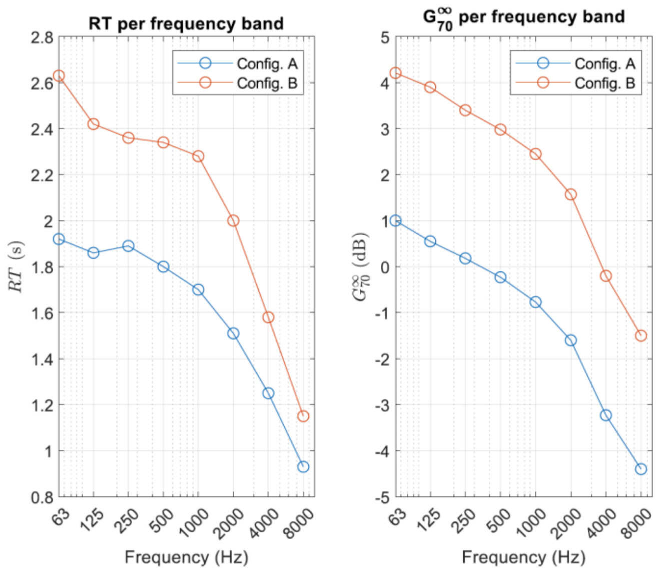

Figure 3: Monaural parameters describing the total reverberated sound field.

For each configuration, 4 spatial energy distributions were synthetised (Figure 4).

- Test 1 : an isotropic case and one without frontal reverberation
- Test 2 : a case with increased lateral reverberation and one with more reverberation from behind. For these stimuli, the lateral and rear decay times were also raised of 0,5 s with the principle of equal energy, that is that the gain in these directions was diminished so that the directional energy remained the same as if RT(rear) and RT(lateral) hadn't been increased.

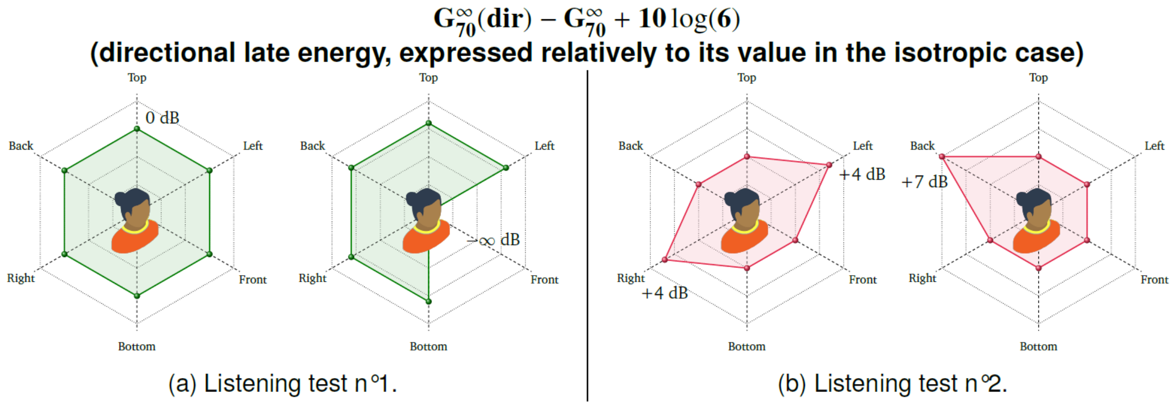

Figure 4: Pairs of spatial distributions of late energy presented during the tests.

The anechoic music extracts used for the tests were :

- a text read in english by a woman speaker (test 1)[13]
- an orchestra recording (test 1, test 2)[6]
- a string trio recording (test 1, test 2)[5].

The stimuli were on average 12 seconds long and all contained a terminal reverberation tail. During a pre-test, subjects noted that an increase of RT in any direction could be noticed only during the terminal decay. On the other hand, an increase of $G_{70}^{\infty}(\text{dir})$ could be heard in the running reverberation.

2.3 Participants

The participants were 9 acousticians from Kahle Acoustics. Half of the subjects could carry out the listening tests with their own set of individual HRTFs. The others used these same HRTFs as generic HRTFs. Thanks to a previous test, the subjects were already familiar with listening to anisotropic reverberant sound fields. They were asked to move their heads while listening to each stimulus. Their thresholds of audibility were not measured.

2.4 Method

During the listening tests, pairs of stimuli ("A" and "B") were successively presented in a Max/MSP interface. Participants could replay them as many times as necessary and almost instantaneously switch between them.

Subjects were asked to detail freely and as far as possible their perceived subjective impressions of the two stimuli. The paper form on which the answers were written included a list of subjective factors (*preference, strength, reverberance, timbre/coloration, clarity, intimacy, envelopment, apparent source width*). The subjects did not systematically mention each of these aspects.
Each person had a single listening session during which pairs were presented in random order, including pairs from tests 1 and 2, as well as other pairs associated with other tests not used here. The average session lasted 40 minutes.

In a second phase, around two weeks after the tests, the subjects listened to the pairs of stimuli again, this time knowing the characteristics of A and B. Their comments brought out a number of elements that were transcribed. In total, the observations on the 1st test (resp. 2nd test) were based on 18 comparisons (resp. 17 comparisons).

Beforehand, the headphone sound level was tuned by 3 participants, so that the produced sound level was considered plausible. For each anechoic music extract, their mean value was chosen and fixed for the tests.

3 OBSERVATION AND DISCUSSION

The chosen method for the tests is not best suited for a statistical analysis of the results, but rather to an exporatory investigation of anisotropic reverberation effects on auditory perception. In this research, we identified the elements presented here by overviewing the responses and discussing them with the participants. Further research is required to establish accurate degrees of correlation.

3.1 Test n°1

In the 1st test, 4 out of 5 subjects found that reduced frontal reverberation improved intelligibility with configuration A case, with the speech signal. With configuration B, the preferences were less clear : the participants felt that there was too much reverberation around them as well as strong reflections from the sides or the rear, which adversely affected the clarity/intelligibility of the source. For the orchestra recording, the subjects all found the difference between the two stimuli subtle, with both configurations.

Therefore, for the same total late energy G_{70}^{∞} and the same early-to-late ratio, intelligibility seems to vary significantly for configuration A. It also seems that the more reverberant the room is (configuration B here), the less intelligibility is dependent on directional variations of the reverberation tail. These observations call into question the relevance of the monaural parameters C_{80}, D_{50} associated with clarity/intelligibility, which are constant here.

Furthermore, 7 out of 18 responses indicate that the reduction in frontal energy provides more envelopment, or more "room impression", for both extracts (speech and orchestra). If we consider the objective criterion for LEV LG_{80}^{∞}, envelopment must indeed be greater for these stimuli, since late lateral energy had to be increased to compensate for the reduction of frontal energy.

Considering only monaural parameters when optimising a room geometry could lead to deteriorated subjective impressions. This first listening test suggests, as an exemple, that an orchestra shell is detrimental to the perception of reverberation by increasing the late energy coming from the stage. A concert hall should therefore be optimised to reduce reverberation on stage and to emphasize it in the main volume. The practical use of spatial parameters is necessary to assess the positive and negative effects of the spatial distribution of reverberant energy in a hall.

3.2 Test n°2

In the 2nd test, a majority of responses (10/17) indicated that lateral reverberation made the source wider and/or more enveloping than rear reverberation. In the most reverberant configuration, the two spatial energy distributions were judged to be not realistic enough, with excessive reflections from the sides or the rear.

It is interesting to note that some subjects' preferences between the two A and B presented distributions were reversed when the same pair of was presented in the other reverberation configuration. For example, one person who had preferred the rear reverberation in configuration A indicated that in configuration B, the rear late energy was too great and considered unrealistic. In the discussion that followed the listening test, the participants reaffirmed these preferences. The spatial distribution of energy G_{70}^{∞}(dir) - G_{70}^{∞}+$10\log(6)$ expressed relatively to the total energy, was identical between configuration A and configuration B, by definition. These differences in preference suggest that spatial parameters expressed as an energy ratio are not appropriate for describing auditory perception of anisotropic reverberation. Dick and Vigeant had mentioned this point[7]. As a consequence, directional energy parameters G_{70}^{∞}(dir) should be
preferred to the ratios G_{70}^{∞}(dir) - G_{70}^{∞}+$10\log(6)$.

A difference in coloration was also observed during this 2nd listening test. The subjects (9 responses out of 17) stressed that the distribution with more rear reverberation was warmer, or conversely that the distribution with more lateral energy was brighter, even nasal. This configuration was also judged louder, and sometimes more “precise” or more “reactive”. These results stem from the characteristics of human hearing and can be read on the HRTF curves: we perceive the high frequencies better from lateral directions. Although hardly surprising, these effects of the anisotropy of reverberation should be taken into account when designing a concert hall.

Additionnaly, several subjects pointed out, especially with configuration B, that the reverberation was no longer realistic because lateral or rear disturbing events, interfering with the direct sound. Several responses from the 1st test with configuration B, for speech, also mention this problem. Lateral/rear reverberation is therefore undesirable above a certain threshold. Although this is unlikely to happen in a traditional hall, an active reverberation system could cause these impressions.

The observations based on the responses must be carefully observed. The auralisations were indeed synthetic, subject to the limits of the model considered. Masking effects due to the early reflections may have occured. Furthermore, reverberation in this research was isotropic by default, while it is not in a concert hall – if only because of the absorption of the seats behind the listener. More generally, Berzborn and Vörlander showed the wide variety of cases that can be observed[2].

The orchestral extract was more appreciated than the trio extract; in the latter the reverberation did not correspond to the perception of a small group in a concert hall with a RT of 1.8 or 2.3 s.

4 CONCLUSION

In this article, two listening tests based on a simple anisotropic reverberation model have been carried out. Participants’ answers provide an idea of the subjective impressions affected by the directional variations of late reverberation : listener envelopment, clarity, reverberance, timbre. The results also suggest that parameters derived from directional energy ratios are not appropriate to describe subjective impressions of the anisotropy of reverberation.

The lesson to be learned from these listening tests is the need to consider spatial parameters in the practice of room acoustics. When confronted with the subjective impressions of acousticians, these parameters could help making progress on subjects that are still poorly understood in room acoustics. Furthermore, at a time when more and more renovation projects require active reverberation systems, the analysis of spatial room responses (SRIR) and the understanding of subjective impressions arising from an anisotropic reverberant field are all the more necessary.

Figure 5: An example of a room with an active acoustics system : Bechstein Hall, London. Architecture by Purcell Architecture Ltd.

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APPENDIX : SPATIAL ROOM IMPULSE RESPONSES (SRIR)

With the development of 3D sound field capturing techniques using microphone arrays, the analysis of the spatial features of the sound field has become a standard for research in audio processing. This analysis is often based on spatial room impulse responses (SRIR), which extend room impulse responses (RIR). A SRIR provides a description of the sound field and its derivatives at a single measurement point. SRIR are generally encoded into the spherical harmonics domain at a certain order L.

Directional impulse responses (DRIR), which describe the incident sound field for a set of specific directions, are calculated from a SRIR using a beamformer $\mathbf{w}$. Beamforming tends to smooth the spiky characteristics of the spatial response.

$$DRIR(\theta, \phi, t) = \mathbf{W}(\theta, \phi) \cdot \mathbf{SRIR}(t) \tag{1}$$

Given a quasi-uniform spherical distribution of directions $(\theta_k, \phi_k)_{1 \le k \le K}$ to retrieve the DRIR, the *Sampling Ambisonics Decoder* (SAD) ensures energy conservation between the spatial response of order L and the directional responses[18].

$$\boldsymbol{w}_{SAD}(\theta_k, \phi_k) = \left(\sqrt{\frac{4\pi}{K}} Y_n(\theta_k, \phi_k) \right)_{1<n<(L+1)^2} \tag{2}$$

where Y_n is the *n*-th spherical harmonics of order L. Note: The order of the spherical harmonics follows the same convention as that of the SRIR.

In this way, it is possible to extend the monaural parameters to all the directions considered. Late reverberation can be described by a simplified model, with a parameterisation of two parameters per direction: the directional reverberation time $RT(\theta_k, \phi_k)$ and the directional late strength $G_{80}^{\infty}(\theta_k, \phi_k)$. The directional late strength corresponds to the directional late energy, calibrated by a direct sound measurement at 10 m distance p_{10m}.

$$G_{80}^{\infty}(\theta_k, \phi_k) = 10 \log \left(\frac{\int_{80\text{ms}}^{\infty} DRIR^2(\theta_k, \phi_k, t) dt}{\int_0^{\infty} p_{10\text{m}}^2(t) dt} \right) \tag{3}$$

In this article, the synthetised reverberation tail had an onset of 70 ms after the direct sound. For the calculus of the late strength (G_{70}^{∞}, G_{70}^{∞}(dir)), the late energy integration time was set at 70 ms instead of the usual 80 ms, and specular reflections with a delay greater than 70 ms were neglected in the late energy.