Discrimination thresholds of the reverberation in large volumes by naïve listeners

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Reverberation is one of the main perceptual dimensions allowing to rate and to discriminate the acoustics of rooms. Several studies concerning its perceptive threshold have been carried out previously. The resulting threshold values are somewhat scattered, varying between 4% and more than 20%. These studies differ in terms of sound stimuli, length of the reverberation, experiment design and experience of the subjects. In this study, a comparison and an adjustment experiments were carried out using three sound stimuli: white noise, male spoken words and an orchestral extract. The room impulse responses used in these comparisons are characterized by frequency-dependent decays. The reverberation time at 1000Hz of the mean impulse response was 1,89s which is representative of a medium size concert hall. The subjects were students with half of them playing a musical instrument regularly. They had no prior experience in terms of perceptual audio testing. A differentiation threshold around 10% is obtained, varying slightly with the experimental conditions and the sound stimuli. The thresholds obtained for speech signals were lower of about 2% than those obtained for white noise and the orchestral piece of music.

1 Introduction

Perceptive dimensions allowing a listener to rate and discriminate the acoustics of a room are few [1, 2, 3, 4]. Three main dimensions can be listed: reverberance (perceived reverberation) [5], spatial impression (source width and listener envelopment) [3, 4] and sound strength [1, 4]. Reverberance can be related to two room-acoustics objective parameters: reverberation time [3, 4] or early decay time [1].

Several studies aim to determine the perceptual threshold of reverberance [6, 7, 8, 9, 10]. The obtained values are somewhat spread, varying from to 3% up to 39%. However, these studies differ in term of tested reverberation time, sound stimuli and experimental set-up and some contradictory results can thus be pointed out.

Concerning the length of the reverberation time, Seraphim [6] found that it has no influence. Karjelainen [7] confirmed this result in one experience but not in another one. Similarly, Karjelainen [7] highlighted an impact of the nature of the sound stimuli on the threshold whereas Frissen *et al.* [10] found no effect. Using music extracts, Meng *et al.* [9] even observed an effect of the used motifs. Outside of other parameters, the experimental set-up has also an influence on the measured threshold [9, 10].

Otherwise, the applicability of these results to real-life room-acoustics could appear somewhat limited. In fact, the created impulse responses in all the presented studies consist in frequency independent exponential decay. On the other hand, the impulse responses recorded in real rooms are generally frequency dependent and their decays can depart from an exponential one.

In this study, more realistic frequency varying impulse responses based on ray-tracing simulation of a concert hall are used. These impulse responses are convoluted with three different sound extract (white noise, human speech and a music extract). The experiment are conducted following two protocols. In the first experiment, the subject must judge the reverberation of two stimuli are equal or not. During the second experiment, the subject must match a varying sound stimuli to a reference.

2 Sound stimuli

2.1 Sound extracts

During the experiments, three different sound extracts, each during 4s, are used: white noise, human speech and orchestral music. The white noise was generated using Matlab. The human speech was recorded in an anechoic chamber. The orchestral extract is an extract of the II movement of the Bruckner's symphony no. 8. It was created by multiplying and mixing anechoic recordings of each instruments [11] as described in [12]. For the humaan speech, the sound energy is concentrated between 100 and 1000Hz whereas it is spread from 100Hz to 4000Hz for the orchestral extract.

2.2 Room impulse responses

The impulse responses are the results of modified results of a ray-tracing simulation [13]. The simulated concert hall is the Groser Musikvereinsaal in Vienna [1] whose acoustic quality is well known. Firstly, the geometry of the hall was created and simulations were carried out using the Salrev ray-tracing software [14]. The measured and computed reverberation times are presented in Table 1, varying between 1.62s and 2.25s depending on the frequency. For each octave band, the slope of the sound decay is then varied after the direct sound between -15% and +15% as a post-processing. The same relative variation is applied to each octave band. The acoustic stimuli are created by convolving the anechoic extracts with the room impulse responses using the auralization [15] software Auralias [16]. To permit a more realistic sound rendering through headphones, head related transfer functions are applied. Moreover, the obtained stimuli are equalized in terms of loudness. Thus, more than 120 sound stimuli lasting 6s are created.

Table 1: (C) Computed and (M) measured [1] reverberation times as a function of the octave band of the Grosser Musikvereinsaal.

Freq. (Hz)	125	250	500	1000	2000	4000
M (s)	2.28	2.17	2.04	1.90	1.80	1.62
C (s)	2.25	2.13	1.94	1.89	1.81	1.62

3 Experimental apparatus

The experiments were carried out using a laptop computer and a Sennheiser HD-25-1 headphones in a small neutral room (without windows). After the training period, each participant was alone limiting the interference of the experimenter. For each experiment and the training period, specific Matlab interfaces were created enabling to read the sound extracts and record the responses. These interfaces also displayed the instructions of the experiments.

4 Training period

Firstly, reverberation was briefly introduced to the subject. After this stage, a training period followed. On a Matlab interface, a pair of stimuli was presented to the subject. He must identify the more reverberant one. A first set included pair with difference of 20% then, after 10 correct answers, a second set with 15% difference was proposed. After, 10 correct answer the training period was ended. In the case of incorrect answer, the same pair was again proposed but with randomly shifting the order of the stimuli.

5 First experiment

5.1 Procedure

A sound pair was presented to the subject and he was asked to identify the more reverberant one or to judge them equal. At the beginning of the process, the reverberation difference is equal to ± 15%. At each correct answer, the difference is decreased, up to 1%. When the answer was incorrect, the process restarted at the beginning (± 15%) For each sound extract (speech, white noise, music), the process started alternatively three times at + 15% and three time at - 15%. The sound extracts were presented randomly to each subject. So, 6 values of the threshold were obtained for each sound extract at the end of the experiment. In average, the experiment lasted 25 minutes. Fig. 1 presents the used Matlab interface.

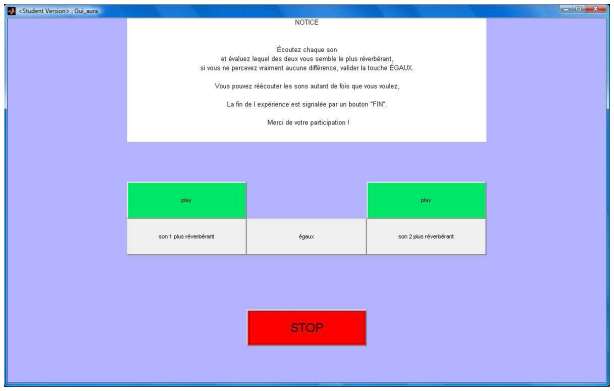

Figure 1: Interface of experiment 1.

5.2 Participants

. 15 subjects participated to this experiment. They reported normal hearing and their average age was about 21.6 years. One third of the subjects plays regularly a musical instrument however, no subject reported to regularly go to non-amplified music concerts.

5.3 Results

The results are presented in Fig. 2. The effect of variation direction seems to have a weak effect on the threshold and slightly lower values can be observed for the speech compared to the other sound extract. The obtained median values are presented in Table 2. A ANOVA-2WAY is used to investigate the effects of the direction of variation and of the nature of sound extract. For the direction of the variation (up or down), a $p - value = 0.741$ is obtained which implies that the the threshold is not affected the direction of the variation. Similarly, a $p - value = 0.569$ indicates that there is no interaction direction/nature of the extract. On the other hand, the $p - value$ for the variable nature of the sound extract is equal to 0.0414. As a post-hoc, a Student test with Bonferri's correction is carried out and permit to observe that the orchestral extract and the speech have significantly different mean values. Otherwise, the same behavior is observed for the subject playing musical instruments compared to the other participants.

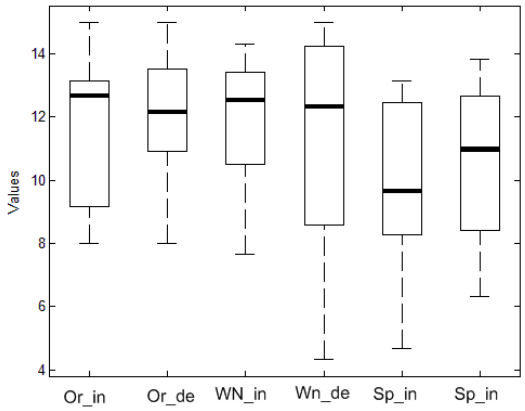

Figure 2: Values of the threshold obtained for Experiment 1 with (Or) the orchestral extract, (WN) the white noise and (Sp) the speech. in indicates that the process was started with a difference equal to - 15% and de indicates that the process started with a difference equal to + 15%.The bold line represents the median value, the box the lower and upper quartiles values, the whiskers the minimum and maximum.

Table 2: Median values of the thresholds obtained with experiment 1 for (Or) the orchestral extract, (WN) the white noise and (Sp) the speech. in indicates that the process was started with a difference equal to - 15% and de indicates that the process started with a difference equal to + 15%.

Or_in	Or_de	WN_in	WN_de	Sp_in	Sp_de
12.7%	12.2%	12.5%	12.3%	9.7%	11%

6 Second experiment

6.1 Procedure

In this experiment, a reference stimulus was clearly indicated and the subject was asked to vary the amount of reverberation of a second stimulus in order to perceptively match the stimulus. When the amount of reverberation is then recorded. The process was carried out 6 times for each sound extract: three times starting from - 15% and three times starting from + 15%. The starting point was randomly chosen. The subject must do the task for each sound extract and again, the order

of sound extracts was randomly chosen. Fig. 3 presents the used Matlab interface.

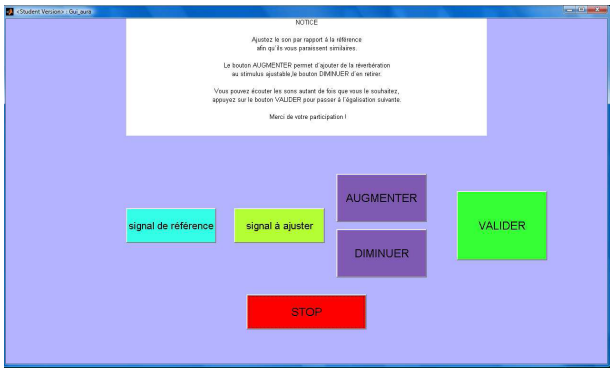

Figure 3: Interface of experiment 2.

6.2 Participants

14 subjects participated to this experiment. They reported normal hearing and their average age was about 22.5 years. No subject reported to play regularly a musical instrument or to go regularly to non-amplified music concert.

6.3 Results

In this experience, the speech extract exhibits again slightly lower values of the observed threshold (Fig. 4). Otherwise, he effect of variation direction seems to be weak apart for the speech extract. The obtained median values are presented in Table 3. A ANOVA-2WAY is again used to investigate the effects of the direction of variation and of the nature of sound extract. The direction of the variation does not affect the obtained threshold ($p - value = 0.644$). On the other hand, the value of the threshold is affected by the nature of sound extract ($p - value = 0.017$), however there is no interaction between the direction of the variation and the nature of the extract. A similar post-hoc analysis to Experiment 1 permits to observe that the speech extract leads to a mean value significantly different than the ones obtained with the orchestral extract and the white noise.

Table 3: Median values of the thresholds obtained with experiment 1 for (Or) the orchestral extract, (WN) the white noise and (Sp) the speech. in indicates that the process was started with a difference equal to - 15% and de indicates that the process started with a difference equal to + 15%.

Or_in	Or_de	WN_in	WN_de	Sp_in	Sp_de
10.3%	10.7%	11.8%	11%	10.3%	7.8%

7 Conclusion

Reverberance, the perceived reverberation by a listener, is one of the mains perceptual dimensions allowing to rate and discriminate the acoustics of rooms. The previous studies were limited to frequency invariant sound decays and often to exponentially decreasing sound decays. In this study, more realistic frequency varying room impulse responses are

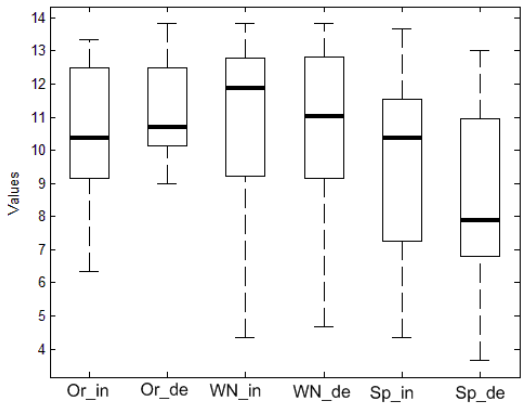

Figure 4: Values of the threshold obtained for Experiment 1 with (Or) the orchestral extract, (WN) the white noise and (Sp) the speech. in indicates that the process was started with a difference equal to - 15% and de indicates that the process started with a difference equal to + 15%.The bold line represents the median value, the box the lower and upper quartiles values, the whiskers the minimum and maximum.

used. The obtained thresholds concerning the reverberance, about 10%, are in a good agreement with those obtained by Frissen *et al.* [10]. However, they observed that the computed value of the threshold are independent on the tested sound. In this study, the speech extract permits to obtain significantly lower values that the orchestral extract or the white noise. On the other hand, the direction of the variation (more or less reverberation) has no effect while Meng *et al.* [9] reported a weak effect on their obtained threshold. Moreover, it can be observed that the obtained values are dependent on the experimental protocol: Experiment 2 allows one to obtained slightly lower values of the threshold compared to experiment 1. It should remembered that the subjects can be considered as naive, without previous experiences concerning perceptual audio testing. Moreover, no subject reported to regularly go to non-amplified concerts.

Acknowledgments

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