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PERCEPTUAL SENSITIVITY TO THE "OPEN WINDOW" IN REVERBERATION

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ABSTRACT

Late reverberation is often considered and modelled as diffuse, isotropic reverberation. However, our experience shows that we can hear spatial anisotropy in reverberation, e.g. when walking past an open door or sitting in front of absorbent surfaces. We studied the perceptual sensitivity to spatial gaps simulating a spatial absorption window, i.e. with total absorption, in otherwise spatially diffuse reverberation. A static situation with the direct sound from the front (0°) and diffuse reverberation from 36 horizontally arranged loudspeakers in an anechoic chamber was used. The spectral and temporal decay of reverberation reflected an average room. The gap was located at either 0°, i.e. in the direction of the direct sound, or at 90°. A gap of variable azimuthal angle had to be detected using a 3-interval, two-alternative forced-choice paradigm. Gap thresholds were determined with an adaptive paradigm.
Results for noise bursts show highest sensitivity to absorption gaps in diffuse reverberation at the side (~35°) and lowest (70-110° threshold) if the gap is at the front and aligned with the direct sound. Spatial absorption gap detection improved significantly for longer reverberation times. More negative direct-to-reverberant ratios lowered spatial absorption gap thresholds, but the change remained non-significant. In about a quarter of trials and conditions, thresholds of 20° or lower were obtained, indicating that horizontal loudspeakers should not be spaced coarser than 30° when reproducing reverberation.
Keywords: *spatial hearing, virtual acoustics, reverberation, interaural correlation, room acoustics*

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1. INTRODUCTION

The concept of the "open window", or equivalent absorption area, in room acoustics states that the absorption of all surfaces in a room can be collapsed into one area with total absorption. In statistical room acoustics, the equivalent absorption area together with the volume is sufficient to estimate the reverberation time (RT60) [1, 2]. In doing so, a diffuse sound field with isotropic energy distribution is assumed. In reality, the diffuseness depends on the source and receiver position in the room: near an absorptive surface the reverberant sound field will be energetically biased since the reflected and diffuse energy from the direction of that surface is reduced. The extreme case is a surface with total absorption, the "open window", which is considered here (absorption only without diffraction effects). How large does the open window need to be to be audible by causing a change in the reverberant sound field?

The question is relevant from a psychoacoustics and room acoustics point of view, and also for room acoustics simulations: when simulating reverberation, discrete spatial (loudspeaker) channels are often used to reproduce diffuse sound field components. Their number should be low in order to keep computational complexity low. Kirsch et al. [3] have studied the change in interaural correlation and the perceptual threshold for detecting the change caused by reducing the number of spatial channels in a spatially uniform way. They concluded that 12 reverberation sources are required in a uniform, 3-dimensional loudspeaker arrangement to reproduce an isotropic diffuse sound field, and up to 24 reverberation sources when one wall was totally absorbing [3].

Here, we study the perceptual threshold for detecting a single spatial gap in otherwise diffuse reverberation created by reproduction via a horizontal loudspeaker array with 36 loudspeakers. The width of the gap was determined for different reverberation times (RT60) and direct-to-reverberant ratios (DRRs).

2. METHODS

2.1 Setup

Experiments took place in the Simulated Open Field Environment (SOFE) installed in the anechoic chamber at TUM [4, 5]. We used its 36 horizontal loudspeakers installed in a square layout at ear height, which were equalized in latency, amplitude, frequency and phase response to be identical in the array center and hence act as a virtual loudspeaker circle with 10° loudspeaker spacing. Participants sat in the center of the array.

2.2 Reverberation

The reverberation was applied through convolution of the stimuli with spatial room impulse responses for each of the 36 loudspeakers. After the direct sound Dirac impulse in the frontal loudspeaker's impulse response, a silent delay-gap of 20 ms was introduced, before the reverberation started. The reverberation tail was based on uncorrelated Gaussian Noise (20 – 20000 Hz) for each loudspeaker channel which was split into 32 one-third octave bands using FFT bandpass filtering. A frequency-dependent exponentially decaying envelope was applied to each noise band to generate a frequency dependent RT60. The frequency distribution was adapted from the reverberation characteristics obtained in a real-world survey of rooms, with longest reverberation times between 200 Hz and 2000 Hz [6].

Different RT60s in the present study were obtained by scaling the frequency-dependent RT60. The RT60s tested were chosen to be 0.4, 1.3 and 2.2 s based on [3].

For the DRRs, 0, -6 and -12 dB were chosen, the latter to have a stimulus with substantial energetic dominance of the reverberation. The DRRs were varied by scaling the reverberation tail relative to the direct sound without changing the decay time RT60. The overall level (with direct sound) was normalized so that it remained the same across the different DRRs to reduce loudness effects.

The gap was applied by silencing the reverberation in the respective loudspeaker impulse responses. This resulted in a small reduction of reverberant energy but not the rate of energy decay. The level reduction was not compensated for since it was negligibly small, 0.5 dB for turning off four of 36 diffuse noise channels. The gap was introduced either in the front (0°) or around 90°.

2.3 Stimuli

The experiment was conducted with two stimuli, a train of noise bursts and a recorded word. The train of noise bursts, or pulse train, consisted of 3 bursts of Pink Noise of 10 ms duration, separated by 200 ms of silence, resulting in a duration of about 0.5 s for the dry signal. The noise was recomputed in every trial and hence for each pulse in the sequence. This resulted in timbre and amplitude changes between each short pulse and across pulse trains, rendering these cues unusable. The noise was normalized to 70 dB SPL.

The second stimulus was a short, frozen speech sample of the word "shape", recorded with a female voice, played at 60 dB SPL.

2.4 Experimental method

A three-interval, two-alternative forced-choice procedure was used. The first interval contained diffuse reverberation on all loudspeakers as reference, while the second and third intervals contained the stimulus with the reverberation gap at equal probability. Subjects chose if the gap was present in the second or the third interval. The width of the spatial gap was adapted with a 3-down, 1-up procedure and the detection threshold obtained as the average over the last four reversals at the smallest step size, 10°. One trial was collected per test condition and participant.

2.5 Participants

A total of 8 people took part in the experiment, six male, two female. Two of these participants were older than the others, having a hearing threshold of 30-40 dB at 4-8 kHz, but normal hearing (≤20dB) at the other frequencies. The other 6 participants (age: 19-30 years, mean age: 23.5 years, SD=3.35) were tested to have normal hearing. Results did not appear to differ for the older participants.

Participants gave informed consent before participating in the study and they received no compensation. The study was approved by the ethics committee at TUM, 65/18 S-KK.

3. RESULTS AND DISCUSSION

3.1 Gap location

The effect of gap location is depicted in Figure 1 for results pooled across all other factors: stimuli, RT60 and DRR. Detection thresholds for the spatial gap are substantially higher for a gap located at 0° compared to a gap at 90°, with medians of 90° and 37.5°, respectively.

The gap in the front at 0° is co-located with the direct sound. Since the direct sound from the front leads to mostly diotic ear signals, the added diffuse reverberation decorrelates the ear signals. As the gap is widened symmetrically around 0°, there is no asymmetry in the reverberant sound field and also the decorrelating effect changes only slightly since loudspeakers from the front which mostly produce correlated ear signals are turned off. This differs for a gap at 90°: widening the gap leads to an asymmetry, and ILDs in the reverberant sound field and changes in interaural correlation of the ear signals since the "most decorrelating" loudspeakers around 90° are turned off.

3.2 Effect of RT60

The effect of varying the reverberation time on spatial absorption gap detection thresholds can be seen in Figure 2. Results are given for the gap at 90° and the pulse train stimulus, with pooling over DRRs. As expected, longer lasting reverberation improves the detectability of the gap as it becomes easier to listen into the reverberation tail in the temporal gaps of the pulsatile stimulus. The mean threshold improves from 52.1° to 42.6° to 34.1° for RT60 increasing from 0.4 s to 1.3 s to 2.2 s, respectively. In light of an interquartile range of about 20°, the improvement appears in the same range. Using a one-way ANOVA, the group effect is significant ($p<0.0062$, $F=5.48$).

3.3 Effect of DRR

Figure 3 shows the effect of varying the direct-to-reverberant energy ratio while pooling over RT60s. At negative DRRs, the reverberant energy dominates the total signal and hence the spatial absorption gap in the reverberant sound field should be easier to detect. For the DRR changing from 0 dB to -6 dB to-12 dB the mean thresholds decrease from 47.1° to 45.0° to 36.7°, respectively. The mean effect of 10° is thus smaller than that of RT60 for the parameter ranges tested and it does not reach significance ($p>0.1628$, $F=1.86$). Nevertheless, at -12 dB DRR, a quarter of the thresholds obtained are

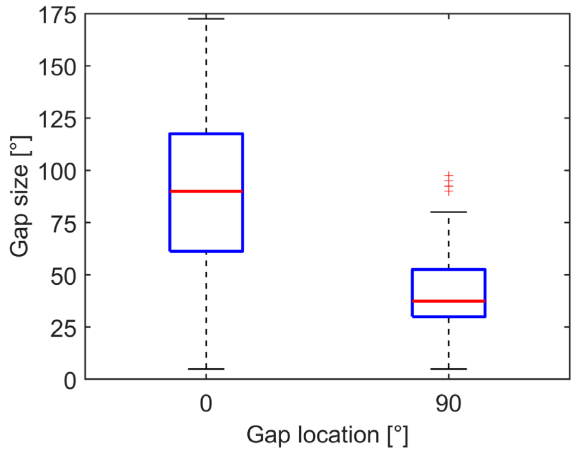

Figure 1. Spatial absorption gap detection thresholds in diffuse reverberation as function of the location of the gap when results are pooled across stimuli, RT60s and DRRs: In the direction of the direct sound, from 0°, gaps are harder to detect than when the gap is at 90° and thus not in the direction of the direct sound. Given are medians, upper and lower quartiles, and bars indicating the most extreme data points with "+" depicting outliers.

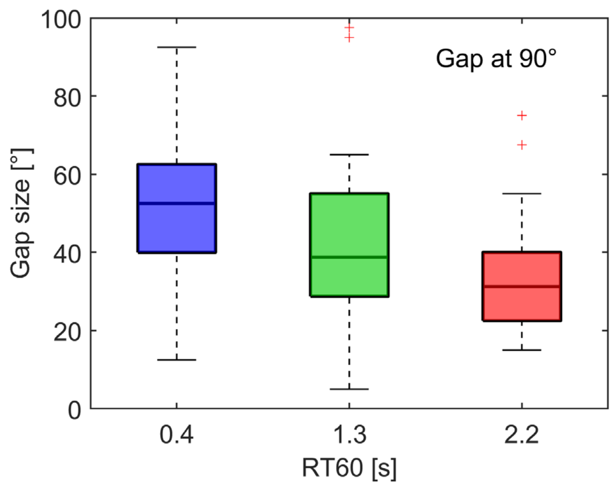

Figure 2. Spatial absorption gap detection thresholds for a pulse train stimulus as function of RT60 when results are pooled over DRRs.

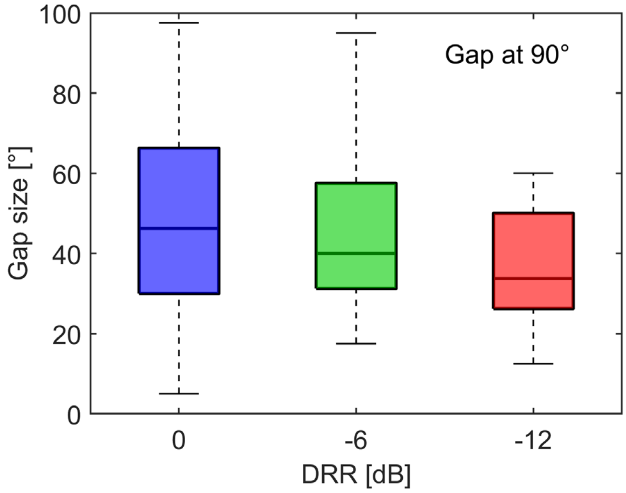

Figure 3. Spatial absorption gap detection thresholds for a pulse train stimulus as function of DRR when results are pooled across RT60s.

at around 24°, showing that a spatial absorption gap from turning off two loudspeakers at 90° can be detected. In other words, a horizontal loudspeaker spacing of 30° will be sufficient in conditions with dominant reverberant energy without audible changes in the reverberation.

4. CONCLUSIONS

We report on an experiment testing the ability to detect a spatial gap in diffuse reverberation in the presence of a direct sound from the front. Spatial absorption gap detection is substantially better if the gap is located at the side (90°) than in the front (0°), where it was co-located with the direct sound. Lower direct-to-reverberant energy ratios and longer reverberation times improve the ability to detect the spatial absorption gap on average, i.e. permit smaller gaps to be detected, but only changes in RT60 led to significant effects. In the more sensitive conditions, spatial absorption gaps of 30° were reliably detected on average (median), although almost a quarter of subjects and conditions detecting also 20° gaps. There was substantial variance in the ability to detect spatial absorption gaps in the reverberant sound field across subjects.

5. ACKNOWLEDGMENTS

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