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Simulating distance cues in virtual reverberant environments

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ABSTRACT
A series of behavioral experiments examined what cues listeners use to judge distance of nearby sources in reverberant spaces. Results show that, in real environments, reverberation aids performance even for sources within a meter of the listeners, where reverberant energy is relatively low compared to the direct sound. When simulating the same conditions using binaural head-related impulse responses, 1) performance in an anechoic environment is at chance level, while performance in reverberation matches real-room data, suggesting that reverberation makes simulated distances more robust; 2) monaural and binaural stimulus presentations produce similar results, indicating that binaural cues are less important for distance perception in reverberant environments. Finally, listeners cannot judge the distance of high-frequency medial stimuli with accuracy. For these stimuli, overall level is the only available distance cue, so distance judgments will only be reliable if distal stimulus level is constant.

INTRODUCTION
For sound sources within reach of a listener, interaural level differences (ILD) vary with both the direction and distance of the sources [1, 2]. This cue is absolute in the sense that the mapping from ILD to distance does not change with source content or environment, unlike relative cues such as the overall level of the received stimulus. Previous localization experiments performed in anechoic space suggest that listeners use ILD cues to judge source distance [3]. In reverberant environments, an additional distance cue is available, related to the direct-to-reverberant energy ratio ([D/R, [4]) although D/R per se may not be the cue used by listeners [5]. Distance information in the D/R may be relatively weak for sources near the listener, because relatively little reverberant energy is received at the ears. Experiment 1 compares distance perception for nearby sources in anechoic and reverberant environments.

Virtual acoustics techniques can be used to simulate distance of sound sources and to achieve precise stimulus control [6]. The remaining two experiments use this technique to manipulate available cues when judging distance. In Experiment 2, monaural and binaural performance is measured in anechoic and reverberant environments. Results are compared to those from the real environment to determine the relative contributions of ILD and reverberation cues. Experiment 3 looks at how performance depends on the center frequency of the stimulus.

EXPERIMENT 1: REAL ENVIRONMENTS - ANECHOIC VS. REVERBERANT SPACES
Distance judgments in reverberation were collected and compared to anechoic data from a previous study using similar methods [3]. Because the reverberation has a relatively low intensity compared to the direct sound for sources near the listener, we hypothesized that performance would be similar in the two environments.

Methods
Seven subjects participated in Exp. 1, which was performed in a small classroom. The stimulus was a train of five 150-ms 200-8000-Hz pink-noise bursts with 30-ms gaps, presented from a small speaker placed at random locations in the listener's right hemifield, within 1 m of his/her head. For each trial the presentation level was first adjusted so that the level at the center of the head was approximately constant and then roved by ±5 dB to eliminate overall level at the ears as a cue. Listeners indicated the perceived source location by pointing with a wand. Electro-magnetic trackers were attached to both the sound source and the pointing wand, recording the source and response locations. Data were binned by the cone-of-confusion angle (i.e., the

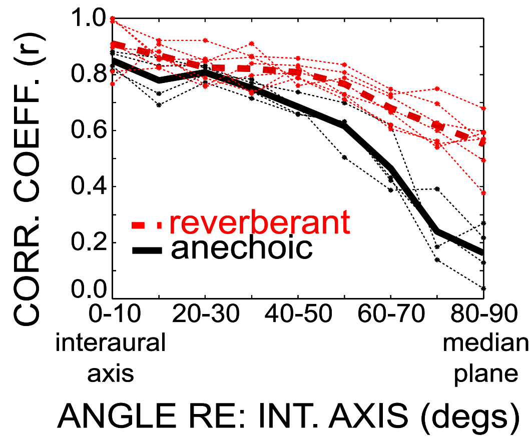

Figure 1. Correlation between source and response distances as a function of lateral angle. Thin lines show individual subjects. Thick lines are the across-subject averages. [3, 7]

angle between the inter-aural axis and the source/response location, with respect to the center of the head). The correlation coefficient between the logarithms of actual and response distances were then computed within each bin.

Results

Figure 1 shows these correlation coefficients as a function of the lateral angle for both anechoic and reverberant environments [3, 7]. For sources near the interaural axis, performance is similar in both environments, suggesting that reverberation adds little information over that provided by ILDs in the anechoic environment. However, it is difficult to determine whether listeners use binaural cues, reverberation, or both cues for these lateral angles. Sources near the midline are judged much more accurately in reverberation, indicating that listeners use reverberation-related cues for sources near the medial plane, where ILD cues are weak.

EXPERIMENT 2: VIRTUAL ENVIRONMENTS - BINAURAL AND REVERBERATION CUES

This experiment investigates the relative contributions of binaural and reverberation cues to distance perception in virtual environments, for both monaural and binaural presentations.

Methods

Seven subjects participated in Exp. 2. Individually measured head-related impulse responses (HRIR), recorded in the same room in which Exp. 1 was performed, were used to generate virtual auditory stimuli that were presented over headphones. Pseudo-anechoic HRIRs were derived from the reverberant HRIRs by windowing out the reverberant tails. In the monaural condition, only the right ear signal was presented. Seven distances were simulated, logarithmically spaced between 15 and 100 cm. Two directions were used: medial (from directly ahead) and lateral (from locations along the right interaural axis). The same noise-burst stimuli were used as in Exp. 1. The listener was seated in front of a computer screen showing a top-down-view of a person with his/her arms outstretched and a circle indicating 1 m distance (Fig. 2A). The listener indicated the perceived source location by pointing and clicking at the desired location with a computer mouse. Four conditions were simulated: all combinations of anechoic or reverberant environment and monaural or binaural presentation. Condition and direction were selected at random and held fixed for each block of 70 trials.

Results

Figure 2B shows the correlation between the logarithms of actual and perceived distances as a function of the simulated environment (anechoic vs. reverberant), mode of presentation (monaural vs. binaural), and the source lateral angle (medial vs. lateral) [8]. Distance perception is generally at or below chance for all anechoic conditions, including the binaural lateral condition for which performance was above chance in the real environment (see Fig. 1). In reverberant conditions, performance for medial sources is worse than for the lateral sources. The medial binaural performance tends to be slightly better than the medial monaural performance, even though medial binaural differences are small. Finally, lateral binaural and monaural results are very similar.

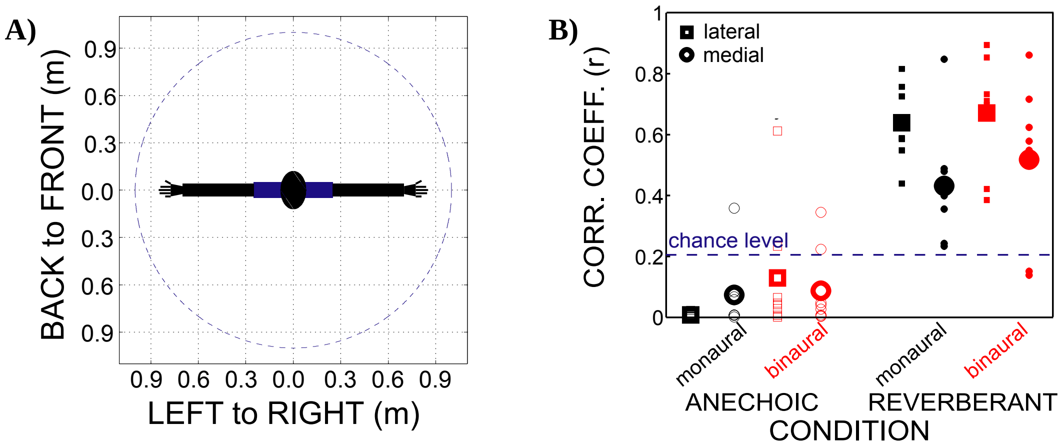

Figure 2. A. Computer screen display. Subjects indicated the perceived source location using a mouse. B. Correlation between source and response distances for each condition. Small symbols represent individual subjects. Large symbols are across-subject averages. [8]

Correlation coefficients from the virtual anechoic environment (Exp. 2) do not match those from the real anechoic environment (Exp. 1). This difference may be due to technical limitations of the simulation or to listeners having difficulty interpreting the virtual source locations. Listeners in many previous studies reported difficulties “externalizing” simulated sources, although listeners cannot always tell whether a sound came from a real or virtual source [10]. The match between the real and virtual reverberant conditions (Exp. 1 vs. Exp. 2) is good, suggesting that a simulation that includes reverberation is more robust than a simulation that does not [11].

Given the good match between real and simulated reverberant results, an alternative explanation for the mismatch between real and simulated anechoic space is that the listeners were influenced by the fact that the different simulated room conditions were interleaved. It is possible that if the listeners consistently were presented with a binaurally simulated anechoic environment, performance would be better.

The similarity of the correlation coefficients for monaural and binaural conditions in Fig. 2B suggests that binaural distance cues, available for the lateral sources, were not very influential on performance for the virtual stimuli (Exp. 2), even though they were important in a real anechoic environment (Exp. 1). A follow-up experiment was performed to verify that the binaural cues were available to the listeners [8]. In the follow-up, only the anechoic binaural lateral condition was tested and the listeners were provided with feedback. Performance improved dramatically, suggesting that the ILD cue is available, but was not used by the listeners as a distance cue in the virtual environment.

EXPERIMENT 3: VIRTUAL ENVIRONMENTS - EFFECTS OF SPECTRAL CONTENT

Results of Exp. 2 suggest that the same reverberation-related cue is used for both frontal and lateral sources. Exp. 3 explored the dependence of this reverberation cue on the stimulus center frequency. Since D/R changes with source distance are fairly similar for medial and lateral sources [12], it was expected that any frequency dependence on distance perception would be similar for medial and lateral sources.

Methods

Six subjects participated in Exp. 3, which was similar to Exp. 2 except for the stimuli. Single 300-ms-long noise bursts were used, with a bandwidth of 200 Hz and a center frequency of 0.4, 3, or 5.7 kHz. The noises were simulated at one of nine distances logarithmically spaced between 15 and 170 cm. The presentation level was first equated at the right ear and then roved by ±5 dB. The experiment was divided into runs of 45 trials in which the stimulus type and direction were held constant.

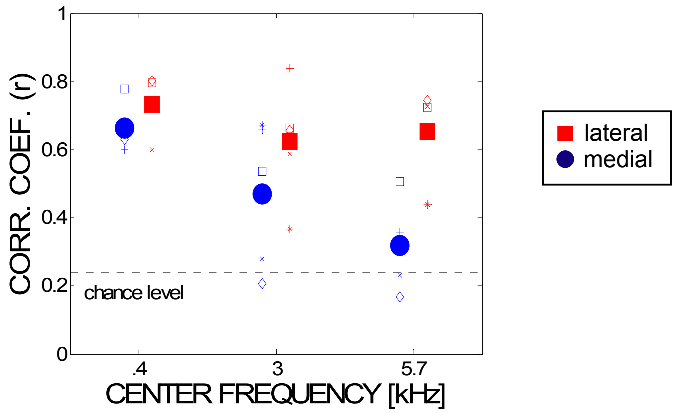

Figure 3. Correlation coefficient between source and response distances as a function of stimulus center frequency. Small symbols represent individual subjects. Large symbols are across-subject averages. [13]

Results

Figure 3 shows the correlations between the logarithms of actual and perceived distance as a function of the stimulus center frequency and the source lateral angle. Performance is always best for the low-frequency stimuli, for which the lateral-source performance is only slightly better than the frontal-source performance. For the lateral sources, performance declines at the medium frequency, but is equal at the medium and high frequencies. On the other hand, for the medial sources, the degradation in performance from the medium to the high frequency is approximately the same as from the low to the medium frequency.

The low-frequency performance in Exp. 3 is comparable to the results of Exp. 2, suggesting that distance perception for broadband stimuli is dominated by the low-frequency spectral content. This conclusion is also supported by the decrease in performance for stimuli centered at the medium and high frequencies.

On the other hand, the difference in the effect of stimulus center frequency between the frontal and lateral sources is not consistent with the results of Exp. 2, which suggested that the same reverberation-related cues are used for both medial and lateral sources. In Exp. 3, the medial-source correlation is less than 0.5 for stimuli with center frequencies of 3 and 5.7 kHz, while it never drops below 0.6 for the lateral sources. This discrepancy may arise because the simulated environment changed between runs in Exp. 2, while the same simulated reverberant environment was used consistently throughout Exp. 3. As a consequence, listeners may have adopted the strategy of using the ILD cues for high-frequency lateral sources in Exp. 3, but not relied on these cues in the broadband binaural condition in Exp. 2.

DISCUSSION AND CONCLUSIONS

These results have implications for the design of an auditory display. 1) Reverberation can provide a robust distance cue in almost all conditions. 2) Listeners use ILD as a nearby-source distance cue in real anechoic environments, but may rely less on ILDs in simulated anechoic or reverberant environments, especially when different environments are interleaved in time. This explanation is consistent with recent studies of learning and adaptation to room reverberation, which suggest that a consistent room simulation is necessary for listeners to achieve good performance [14, 15, 16]. 3) Reverberation provides only weak distance cues for medial sources that do not contain low frequencies. Given that medial sources also do not contain strong ILD cues, relative cues like the overall level are the only cue available to indicate source distance of medial sources.

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