DISTANCE PERCEPTION OF NEARBY SOURCES LOCATED AROUND THE SUBJECT IN ECHOIC ROOMS

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ABSTRACT

Distance perception is typically examined for sources varying in distance, and sometimes also in azimuth. However, very few studies have considered sources varying simultaneously in all three dimensions. Santarelli et al. [1] realized an experiment in a reverberant classroom in which subjects were asked to point to the perceived position of broadband-noise sound sources presented from a random location in the right hemifield within 1 m of the subject's head. Here, a new analysis examines distance responses for source location varying in all three dimensions. After binning the data into two distance bins (split at 50 cm) and 25 directional bins (combinations of 5 lateral angles and 1, 4, or 8 polar angles), mean response distances were determined on a logarithmic scale. On average, distances were underestimated by approximately 10%. However, there was a complex interaction. For far sources, there was a pattern of distance underestimation above the subject (up to 30%) and overestimation below (up to 25%) that was largest near the medial plane. For the near sources, only the overestimation of the below-the-subject sources was observed. Thus, distance representation appears to be distorted more in elevation than in the previously examined dimensions.

Keywords: *3-D sound localization, distance perception, nearby sources*

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1. INTRODUCTION

Most experiments examining sound localization in distance have considered only distances greater than 1 meter. At distances less than 1 m (proximal region), however, there are important distance-dependent changes in the binaural and spectral characteristics of the sound reaching the ears, available even in anechoic space. Duda and Martens [2] and Brungart [3] argue that large interaural level differences (ILDs) are a distance cue for near sources. In regular rooms, additional reverberation-related distance cues, like the direct-to-reverberant energy ration (DRR), are available [4]. The current study examines distance perception in the proximal region when reverberation-related cues are available.

Brungart and Durlach [5] performed an experiment in anechoic room in proximal region and showed that distance localization performance is generally better than has been reported in the region at distances greater than 1 m (distal region) experiments and is strongly dependent on azimuth. Santarelli et al. [1] performed similar experiments in reverberant room in proximal distance and the results suggest that subjects use a cue that varies with both *lateral angle* and *distance* when making distance judgements in a reverberant environment. Here, the Santarelli et al. data are analyzed in the interaural polar coordinate system to examine how source position varying in all three spatial dimensions influences the bias in distance judgements.

2. SANTARELLI ET AL. EXPERIMENT

Full description of the experiment is provided in Santarelli et al. [1]. Seven subjects (2 female, age range 22 – 44 years) participated in the study. Six had normal hearing, one had marginal high-frequency loss. Subjects were seated in the middle of a 14' x 20' rectangular classroom with a carpeted floor and hard walls. Reverberation time T60 was approx. 250 ms. Experimenter and experimental computer were also inside the room. Stimulus consisted of five 150-ms long pink noise bursts separated by 30 ms silence, with level equalized at the head (to overcome distance effects) and additionally rowed by ±7.5 dB. On each trial, it was presented from a random location in 1-m diameter hemisphere to right of subject (see Fig. 1). Subjects' task was to listen to the target with eyes closed while the experimenter placed a point source at the desired location and presented the stimulus. After the experimenter removed the source, the subject pointed to the perceived sound source location using a hand-held wand. Electromagnetic tracker on the sound source and the wand recorded the stimulus and response locations in 3D. The experiment consisted of approximately 1000 trials, performed over several sessions.

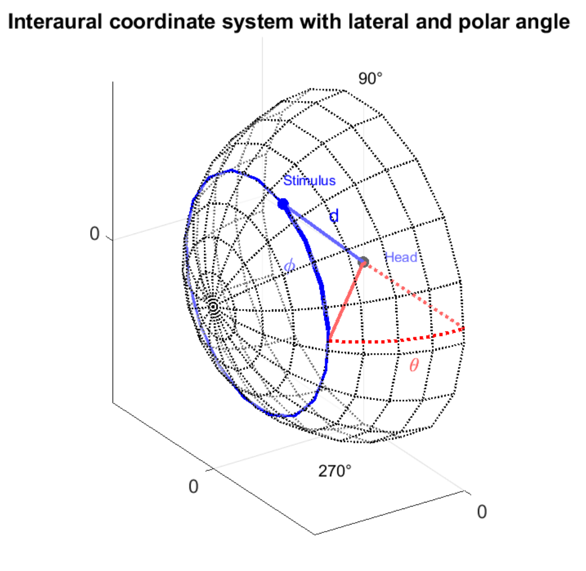

Figure 1. Hemisphere centered at the subject's head (black point) in which stimuli were presented. Stimulus (blue point) has lateral angle θ (0° – 90°; red), polar angle ϕ (0° - 360°; blue) and distance d (d ≤ 100 cm) from the center of the head. Subject facing θ = 0° and ϕ = 0°.

We evaluated the results using the interaural polar coordinate system (Fig. 1) which allowed us to track the dependence of the distance responses simultaneously on the lateral and polar angles, as well as on source distance. The data were binned into 50 bins by dividing them by distance (closer than 50 cm and farther than 50 cm) and direction (25 bins). The directional bins were combinations of lateral angle (5 regular intervals centered at θ = [9, 27, 45, 63, 81°]) and polar angle (one bin for θ > 72°, 4 bins centered at ϕ = [0, 90, 180, 270°] for θ in range of 36 to 72°, and 8 bins centered at ϕ = [22.5 67.5 112.5 157.5 202.5 247.5 292.5 337.5°] for θ < 36° (see upper panels of Fig. 3). We evaluated biases using a log-log scale (log10(response distance) – log10(stimulus distance)), also showing the relative underestimation or overestimation in percent. Repeated measures ANOVA was used to analyze the data with Box-Geissler-Greenhouse epsilon used to correct for potential violations of the sphericity assumption. In some analyses and in ANOVA, only 4 polar bins were used for for θ < 36°, obtained by merging nearby bin pairs such that the resulting bins were centered at the same locations as used for θ in range of 36 to 72°.

3. RESULTS

The individual response data of all subjects are shown in Fig. 2 in which the response bias is plotted as a function of the actual distance on logarithmic scale for each of the 25 directional bins. In general, there is a clear correspondence between the stimulus and response distance. However, there are also biases that vary from one directional bin to another (e.g., with a lot of underestimation for ϕ = 90° and overestimation for ϕ = 270°).

Figure 3 shows the bias data from Fig. 2 averaged within each directional and distance bin for each subject and then collapsed across subjects, separately for the nearby (d < 50 cm) and far (d > 50 cm) sources (columns). The top row shows spherical plots in which the lateral and polar angles correspond to the side view of the hemisphere, as shown in Fig. 1, and the distance biases in each bin are shown by color, as well as by a radial position of a point shown within each bin (green color and dotted line corresponds to no bias). The bottom row shows the same data as a function of lateral angle and parametrized by the polar angle (only considering 4 polar angle bins for all lateral angles smaller than 72°).

Two ANOVA analyses were performed, corresponding to the data arranged in the upper vs. lower panels of Fig. 3. In the first ANOVA, the bias was analyzed for the factors of Distance (2 levels) and Direction (25 bins). It

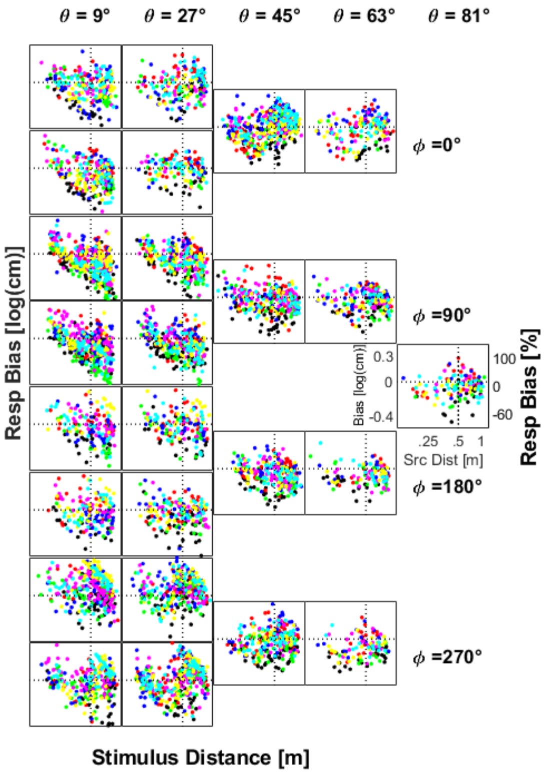

Figure 2. Response bias as a function of actual source distance shown on a log scale separately for the 25 directional bins. The columns represent different lateral angles, and the rows different polar angles. Vertical line indicates d=50 cm used to bin the data in distance. Dots of one color represent all individual data for one subject.

found a main effect of Direction ($F(24, 144)=7.46$, $p<0.001$) and an interaction Direction x Distance ($F(24, 144)=8.01$, $p<0.001$), confirming that the pattern of biases depended on both factors. To assess the dependence of data on the lateral and polar angles, the second ANOVA excluded the most lateral bin ($\theta > 72°$) and for the remaining 4 lateral bins it only considered the 4 polar bins as shown in the lower panels of Fig. 3. A 3-way ANOVA with factors Distance (2 levels), Lateral Angle (4 levels) and Polar Angle (4 levels) found a main effect of Polar Angle ($F(3,18)=16.48$, $p<0.001$) and interactions Distance x Polar Angle ($F(3,18)=17.99$, $p<0.001$) and Distance x Lateral Angle ($F(3,18)=10.18$, $p<0.001$). For the nearby sources the dependence of biases on lateral angles was similar across the polar

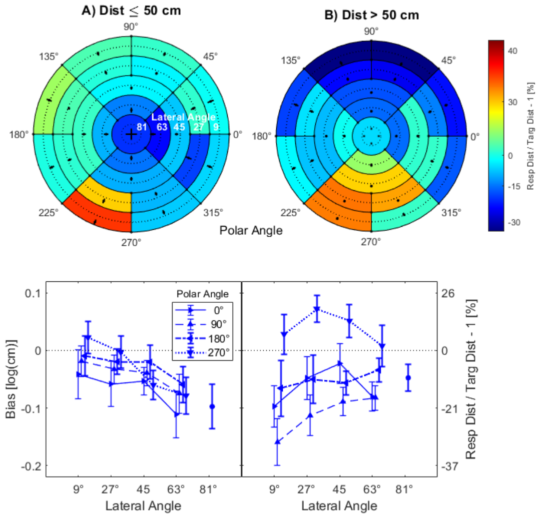

Figure 3. Across-subject mean (±SEM) bias in distance responses analyzed logarithmically in 2 distance bins (columns A vs. B) and 25 directional bins. The upper panels use a spherical plot corresponding to the surface of the hemisphere shown in Fig. 1, with 5 lateral angle and 1, 4, or 8 polar angle bins. The response bias is indicated by color of each patch, or by radial offset of the point shown in each bin (range matching the -40 to +30 % range of the color bar). In the lower panels, the data are rearranged and plotted as a function of lateral angle and parametrized by the polar angle (with 4 polar bins considered for $\theta > 72°$).

angles, with more underestimation at more lateral angles (downward trend in all lines of panel A). Considering the polar angles, the underestimation was the strongest for the frontal stimuli (solid line), while for the stimuli below the subject the trend switched to slight overestimation (dotted line at $\theta = 9°$ in panel A). In contrast to the nearby sources, for the far sources the effects were much stronger (vertical spread of data is larger), indicating a large dependence of distance biases on the polar angle. Specifically, the targets above listener are strongly underestimated (dashed lines in panel B) while the sources below the listener are overestimated (dotted lines), such that both of these trends tend to decrease with the lateral angle. For the sources in front and behind the listener, as well as for the most lateral sources (θ = 81°), there only is a slight, approximately constant underestimation (solid and dash-dotted line). The largest dependences on the polar angle appear to occur near the median plane (for lateral angle θ < 36°). While the bottom panels of Fig. 3 only consider data split into 4 polar angles in this region, the spherical graphs in the upper panels show these data separated into 8 bins. Here, the most noticeable difference is for the data above and below the listeners. While the above-the-subject data are in general very similar (equal shades of blue) for the polar bins centered at 67.5° and 112.5°, suggesting that the responses are equally perceived as too close for sources in front and behind the frontal (coronal) plane, for the below-the-subject data the overestimation tends to be larger behind the lateral vertical plane (red and orange patches are mostly in the polar bin centered at 247.5°). And these biases can reach from overestimation by 40% for the nearby behind-frontal-plane sources (red patch in panel A), to underestimation by more than 30% (dark blue patches in panel B).

4. DISCUSION AND CONCLUSION

The current study examined biases in distance perception for nearby sources varying in location in all three dimensions in reverberation. For sources in the horizontal plane the results don't vary dramatically, with an overall underestimation (approximately -10%) that tends to increase for nearby lateral sources (-20% for θ = 81° in panel A) and appears to be stronger in front than behind the listeners (dash-dotted vs. solid line in panel A). This result is not consistent with nearby studies in the virtual environment, where nearby sources tend to be overestimated, especially for the frontal sources [6] (however, the relative difference, i.e., that the lateral sources are perceived relatively closer than the frontal ones, is consistent). Interestingly, even in real anechoic environments, subjects tended to overestimate the nearby sources, contrary to the current results [6]. Thus, it appears that it is the reverberation-related cues in real environments that cause the subjects to judge sources closer.

For the far (d > 50 cm) sources above the listeners, the underestimation became much stronger (up to -30%). This is unexpected given that the acoustic cues are largely similar for the sources at this polar angle compared to the ones in front or behind the listener. The spatial map might be warped for these sources, as there is much less exposure to sources coming from above at distances less than 1 m (similar to non-uniformities reported in azimuthal representation, e.g., in [7]). Also, it is possible that the response technique introduced some bias, as it might be more laborious to respond above the subject. However, no such biases were reported in the anechoic real environment which used the same response method [5].

Finally, for the sources below the listener's head, there is a general overestimation, in particular for the farther-away sources, that extends in laterality not only directly below, but also to the more lateral sources (up to θ = 45°). This spatial region is unique in that many locations are obstructed by the listener's body and there is also likely a lot of acoustic interaction with the body. However, the overestimation appears to be the strongest behind the listener's medial vertical plane where the body obstruction is not expected to have a larger impact. Even though the anechoic study of Brungart and Durlach [4] did not specifically analyze this effect, from the illustrative subject shown in the study there appears to be such overestimation also in anechoic condition. So, it appears that the effect, again, is caused by a perceptual warping of the space [8], perhaps caused particularly by the fact that we typically do not hear sounds coming from below us at distances other than the ones of our feet (i.e., around 1.5 – 2 m).

In summary, these results illustrate that auditory distance perception of nearby sources is highly non-isomorphic, with the largest distortions in the vertical dimension. Open questions remain as to which cues cause these distortions and how do these biases generalize to larger distances and different stimuli and environments.

5. ACKNOWLEDGMENTS

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