Auditory localization of nearby sources. II. Localization of a broadband source

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Although many researchers have examined auditory localization for relatively distant sound sources, little is known about the spatial perception of nearby sources. In the region within 1 m of a listener's head, defined as the ''proximal region,'' the interaural level difference increases dramatically as the source approaches the head, while the interaural time delay is roughly independent of distance. An experiment has been performed to evaluate proximal-region localization performance. An auditory point source was moved to a random position within 1 m of the subject's head, and the subject responded by pointing to the perceived location of the sound with an electromagnetic position sensor. The overall angular error (17°) was roughly comparable to previously measured results in distal-region experiments. Azimuth error increased slightly as the sound source approached the head, but elevation performance was essentially independent of source distance. Distance localization performance was generally better than has been reported in distal-region experiments and was strongly dependent on azimuth, with the stimulus–response correlation ranging from 0.85 to the side of the head to less than 0.4 in the median plane. The results suggest that the enlarged binaural difference cues found in the head-related transfer function (HRTF) for nearby sources are important to auditory distance perception in the proximal region. © *1999 Acoustical Society of America.* [S0001-4966(99)04310-6]

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INTRODUCTION

Although human sound localization has been studied extensively in the past century, little is known about the spatial perception of nearby sources. The majority of experiments examining directional sound localization have been conducted at distances greater than 1 meter. In this region, the overall amplitude of the sound reaching the ears varies with distance, but the binaural and spectral cues that are used for directional localization are roughly independent of distance. At distances less than 1 m, however, there are important distance-dependent changes in the binaural and spectral characteristics of the sound reaching the ears. It is possible that these systematic changes allow listeners to make accurate judgments about source distance for nearby sources. Since nearly all of the perceptually relevant distance-dependent changes in auditory localization cues occur at distances less than 1 m, we will define this region as the ''proximal region,'' and the region at distances greater than 1 m as the ''distal region.''[1]

This study examines localization accuracy in the proximal region in azimuth, elevation, and distance, and attempts to relate the findings to the proximal-region head-related transfer function.

I. BACKGROUND

The basic mechanisms of directional sound localization are well documented. In the horizontal plane, interaural difference cues have long been recognized as the dominant localization cues. Lord Rayleigh, in his famous ''duplex theory'' (1907), observed that interaural time differences (ITDs) and interaural level differences (ILDs) provide salient information about the lateral position of a sound source. According to the duplex theory, ITDs dominate low-frequency sound localization, while ILDs dominate high-frequency sound localization. The ITD and ILD are important localization cues, but they cannot distinguish between sources located in the so-called ''cones-of-confusion,'' where the interaural difference cues are constant, without exploratory head motions (Wallach, 1939; Perrett and Noble, 1997). Additional information is provided by the complex geometry of the pinnae, which filter the sound reaching the ear with a directionally dependent transfer function at high frequencies (above approximately 4 kHz). When some *a priori* information about the spectrum of the source is available, pinna filtering allows listeners to resolve front–back confusions (Musicant and Butler, 1984; Oldfield and Parker, 1986) and can provide substantial information about the azimuth of a sound source when binaural cues are completely eliminated by unilateral deafness (Slattery and Middlebrooks, 1994). Perhaps most importantly, pinnae cues allow listeners to judge the elevation of the sound sources (Roffler and Butler, 1968). All of the localization cues believed to be relevant to directional localization are included in the head-related transfer function (HRTF), which is the transfer function from a sound source to the eardrums of the listener. The HRTF includes the effects of diffraction by the head, neck, and torso, as well as the spectral shaping by the pinna.

The mechanisms that allow listeners to determine the

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distance of a sound source are less understood than those that allow directional localization. The most salient auditory distance cue under most conditions is the amplitude cue: the pressure of a spherically radiating sound wave is inversely proportional to the distance from the source. Spectral cues also play a role. Atmospheric absorption effectively low-pass filters sounds that propagate great distances, and low-frequency sounds propagate more effectively than high-frequency sounds around obstacles in a room. Both of these effects tend to cause more distant sound sources to appear low-pass filtered relative to closer sound sources, and may provide a spectral distance cue (Little, Mershon, and Cox, 1992). Amplitude and spectral-based distance cues are sufficient for judging changes in the relative distance of a sound source, but can only be used to make absolute distance judgments when the listener has *a priori* knowledge about the characteristics of the source. The ratio of direct to reverberant energy has been proposed as a possible absolute distance cue for localization in rooms (Mershon and King, 1975; Lounsbury and Butler, 1979; Butler, Levy, and Neff, 1980), and distance judgments in a reverberant environment are mildly correlated with source distance (Mershon and Bowers, 1979). Under free-field conditions with an unfamiliar source, distance perception is extremely inaccurate, and several researchers have reported that distance judgments in these conditions are effectively uncorrelated with the actual source position (Coleman, 1963; Mershon and Bowers, 1979; Holt and Thurlow, 1969; Gardner, 1969). A comprehensive review of distal-region localization is provided in Middlebrooks and Green (1991).

One aspect of auditory localization that has received almost no attention is the localization of sources close to the head. As early as 1911, Stewart recognized that interaural level differences increase significantly when a source approaches within a few centimeters of the head, while the interaural time delay is roughly independent of distance (Stewart, 1911a, 1911b). Stewart modeled the head as a rigid sphere with ears at diametrically opposed locations on its surface and used theoretical predictions of the sound pressure on the surface of a sphere to predict the ILD and ITD as a function of source distance and direction. Hartley and Fry (1921) manually tabulated these values at a variety of locations, and Coleman (1963) cited the increased ILDs for nearby sources as a potential auditory distance cue in the proximal region. Brungart and Rabinowitz (1996) have published a formula for evaluating proximal-region HRTFs using a sphere model and re-examined the possible use of proximal-region ILDs as a distance cue, and Duda and Martens (1998) have measured the range dependence of the HRTF for a model of the head based on a bowling ball. Each of these studies found that interaural level differences increase dramatically when the source is near the head, while interaural time delays increase only slightly for nearby sources.

In the past year, proximal-region HRTFs have been measured with a manikin head and a compact, nondirectional acoustic point source (Brungart and Rabinowitz, 1999). Many of the features of the measured HRTFs were similar to those predicted by the rigid-sphere models of Hartley and Fry and of Brungart and Rabinowitz. The important aspects of the measured HRTFs can be summarized as follows:

(1) The interaural level difference increases dramatically as the source approaches the head when the source is outside the median plane. This increase occurs even at low frequencies where head shadowing is negligible in the distal region. At 500 Hz, for example, the ILD increases from 4 to 20 dB as a source at 90° decreases in distance from 1 m to within a few centimeters of the head.

(2) The interaural time delay is roughly independent of distance in the proximal region. Although the time delay can increase by as much as 100 μs as the source approaches the head, this increase occurs only near the interaural axis, where the ITD is large and sensitivity to changes in the ITD is low.

(3) The magnitude of the HRTF is relatively greater at low frequencies than at high frequencies when the source is near the head. This effective low-pass filtering of proximal-region sources results from a combination of diffraction at the ipsilateral side of the head and increased head shadowing at the contralateral ear.

(4) The high-frequency features of the HRTF that are dependent on elevation are relatively insensitive to source distance. The features of the HRTF that changed significantly with elevation were not strongly dependent on source distance.

(5) As the sound source approaches the head, the acoustic parallax effect shifts some of the high-frequency features of the HRTF at the ipsilateral ear laterally in azimuth. For example, the high-frequency patterns in the HRTF seen at 10° azimuth for a distant source might be most similar to the high-frequency patterns in the HRTF at 45° azimuth for a closer source. This parallax is a direct result of the geometric relationship between the locations of the source, the center of the head, and the ear: the 6–8 cm displacement between the center of the head and the location of the ear has little impact on the location of the source relative to the ear at 1 m, but when the source is only 12–15 cm from the center of the head, the angle of the source relative to the ear can differ from the angle of the source relative to the center of the head by 45° or more. The HRTFs measured on the KEMAR manikin generally exhibit this shift at high frequencies.

These results indicate the existence of unique physical acoustic cues in the proximal region that should be relevant to proximal-region localization. Yet, despite the recognition that localization cues are substantially different in the proximal and distal regions, no studies in the literature have systematically measured proximal-region localization performance. The experiments described here examine auditory localization in the proximal region with a broadband source. In particular, they focus on how localization accuracy changes as a function of azimuth, elevation, and distance in the proximal region. The next section discusses the experimental setup. Directional and distance localization are discussed separately in the following two sections. The last two sections compare the perceptual results to the physical local-

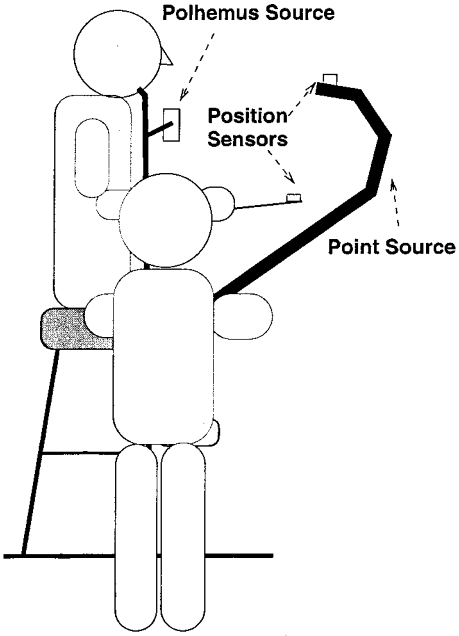

FIG. 1. Experimental setup. The experimenter stood approximately 1.5 m to the right of the listener in an anechoic chamber and manually placed the source at a random location in the subject's right hemisphere. Once the stimulus was produced, the source was moved away and the listener responded by moving a response sensor to the perceived location of the sound. See the text for details.

ization cues found in the HRTFs discussed in the first paper in the series (Brungart and Rabinowitz, 1999), and summarize the overall conclusions of this experiment.

II. METHODS

A. Subjects

Four right-handed male subjects, ages 20–25, participated in the experiment. Three of the subjects were paid volunteers, and the fourth was the first author. All reported normal hearing in both ears. Although three of the subjects had participated in psychoacoustic studies before, only the first author had participated in localization experiments.

B. Apparatus

A simple diagram of the setup for the experiment is provided in Fig. 1. The experiments were conducted in MIT's anechoic chamber. The subjects were seated on a wooden stool located in the center of the chamber, and the stool was supported on the wire-frame floor by a foam-covered plywood platform. The subjects were provided with a chin rest which allowed them to immobilize their heads in a comfortable rest position during the experiments.

An experimenter, who stood approximately 1.5 m to the right of the subject, manually placed the sound source during each trial. The sound source consisted of an Electro-Voice DH1506 compression horn driver connected to 4 m of tubing with an internal diameter of 1.2 cm. The end of the tube was enclosed in a curved rigid wand constructed of PVC pipe. The curved shape allowed the stationary experimenter to place the source (the end of the tube) at any location in the right hemisphere of the subject with the opening of the source pointing toward the subject's head. The small diameter of the tubing provided a relatively nondirectional sound source at the opening of the tube: the measured 3-dB beamwidth of the source was approximately 120° at 15 kHz.

A Polhemus Navigation 3-Space Tracker position-sensing system measured the stimulus and response location during each trial. The electromagnetic source of the tracking system was mounted on the chin rest approximately 15 cm below and 15 cm to the left of the subject. Although the chin rest was not completely rigid, this arrangement fixed the relative positions of the Polhemus source and the subject's head, and therefore the coordinate system of the experiment was stable relative to the subject's head. One of the position sensors was mounted on the end of a 30-cm wooden rod, which the subject used to make responses. The second position sensor was mounted on the end of the experimenter's wand nearest the opening of the tube. Since it was impossible to place the sensor directly at the opening of the tube without interfering with the sound field, the orientation of the sensor and the offset between the sensor and the tube opening were used to calculate the location of the sound source on each trial. The Polhemus system is accurate within 0.25 cm in the X, Y, and Z coordinates up to approximately 1 m. In order to measure the effect of the correction on the accuracy of the location recording system, the response sensor was placed directly at the tube opening and the location of each sensor was measured by the Polhemus system. These two measurements of location differed by 2–3 cm, which can be considered an upper bound on the vector error of the system.

The control computer was a 386-based PC equipped with a 16-bit stereo sound card (Digital Audio Labs CARDD). One channel of the sound card was connected to a small ear-piece headphone worn by the experimenter. This channel was used to provide information to the experimenter during each trial. The other channel was connected to a power amplifier (Crown D-75), which was connected to the driver of the sound source. The Polhemus head tracker was connected to the PC through the RS-232 serial port, and a response switch was connected through the parallel port. The control computer automated all data recording and stimulus generation tasks in the experiment, and provided timing information to the subject and operator through its internal speaker.

C. Stimulus

The stimuli were sequences of five rectangularly gated 150-ms pulses of noise, separated by 30-ms intervals of silence. The noise waveforms were constructed from white Gaussian noise that was filtered by a finite impulse response (FIR) filter to flatten the irregular frequency response of the point source. In addition, the noise was bandlimited to the frequency range 200 Hz–15 kHz (120 dB/decade roll-off out of band) and low-pass filtered with a 6-dB/octave roll-off above 200 Hz. This roll-off was used to maximize the non-distorted output level of the point source. Five different noise waveforms were stored on the control computer, and one waveform was randomly chosen prior to each trial. This waveform was scaled in amplitude and then repeated five times to generate the stimuli for each trial.

The source was randomly located in the right hemisphere of the subject. Prior to each trial, the control computer read three random numbers, each ranging from 1 to 6, to the experimenter through the earphone connected to the second channel of the sound card. The experimenter used these three numbers to choose the approximate sound source location in azimuth (from near 0° for a 1 to near 180° for a 6), elevation (from near $+90°$ for a 1 to near $-90°$ for a 6), and distance (from 10–15 cm for a 1 to 1 m for a 6). Although the exact placement of the source varied across experimenters and some source locations were inaccessible due to interference by the subject's body or the chin-rest apparatus, this source placement system generated a reasonably broad distribution of source locations throughout the right hemisphere.

Once the source was placed, the control computer recorded the location of the source through the Polhemus tracker, and crudely normalized the amplitude of the stimulus signal to eliminate amplitude-based distance cues. The normalization was based on the distance of the source from the left and right ears of the subject. The correction normalized the amplitude so that the maximum output would occur at a distance of 1 meter. The scaling factor for this correction was

$$\frac{1}{\dfrac{50}{\text{Distance to left ear (cm)}}+\dfrac{50}{\text{Distance to right ear (cm)}}}.$$

The distance to the right ear dominates the scaling factor when the source is near the ear, but the scaling factor also considers the contribution of the left ear to perceived loudness when the source is in the median plane or is relatively distant. In addition to correction for distance, the source amplitude was randomized an additional 15 dB (from 0 to 15 dB in 1-dB steps). The amplitude scaling was accomplished by multiplying the noise waveform file by a scaling factor prior to playback. The maximum amplitude of the stimulus was approximately 59 dBA SPL (as measured by a B&K 4131 microphone) at 1 m, so with randomization and correction the effective stimulus amplitude ranged from 44–59 dBA.

D. Procedure

The experiment was divided into blocks of 100 trials, with each block taking approximately 20 min. At the beginning of each block of trials, the subject placed his head in a comfortable position in the chin rest and the locations of three reference points were recorded using the response sensor: the opening of the left ear canal, the opening of the right ear canal, and the tip of the nose. These locations were used to correct for stimulus distance and to define a vertical spherical coordinate system based on the subject's head, with its origin at the midpoint of the left and right ears, its horizontal plane defined by the locations of the left and right ears and the nose, and its median plane perpendicular to the interaural axis and passing as close as possible to the location of the nose (Brungart, Rabinowitz, and Durlach, 1999). In this coordinate system, azimuth is the angle around the vertical axis, with 0° directly in front of the head, positive values in the left hemisphere, and negative values in the right hemisphere. Elevation is the angle above (positive values) or below (negative values) the horizontal plane. Note that, in this coordinate system, a one-degree change in azimuth corresponds to a shorter distance on the surface of a sphere at high and low elevations than in the horizontal plane.

Each trial was initiated when the control computer read the three source coordinates to the operator through the earpiece headphone. A beep then instructed the subject to close his eyes while the operator moved the source to the appropriate location. Once the source was positioned, the operator pressed a response switch and the control computer initiated the stimulus. First, the location of the source was read to allow for amplitude correction, then the stimulus was scaled and played through the sound source, and finally the source position was read again to verify that no movement had occurred during the stimulus presentation. If the source was stationary during stimulus presentation, the operator moved the source to a rest position and pressed the response switch again. The control computer then generated a second beep, prompting the subject to move the response sensor to the perceived location of the stimulus. The subjects were permitted to open their eyes during the response process, but usually chose not to do so. Once the subject had selected a response location, the operator once again pressed the response switch, and the control computer read the response location, generated three new coordinates for the next stimulus location, and beeped to tell the subject to close his eyes and prepare for the next stimulus. Each trial lasted approximately 12 s.

The response method used in the experiment, which we refer to as ''direct location,'' was the method determined to be the least biased and most accurate among a number of three-dimensional proximal-region response methods considered in an earlier study (Brungart *et al.*, 1999). Using the direct-location method to identify the position of a visual target in the front hemisphere, the mean angular error was 4°. The subjects were also equally accurate at localizing sound sources in the front and rear hemispheres using direct location, indicating that precision does not fall off rapidly outside the visual field. The localization errors with a visual target using direct location were much smaller than those found when localizing sound sources, indicating that the response method probably contributed only a small fraction of the response errors in this experiment.

Although the subjects were asked to keep their eyes closed during the placement of the source, there were some extraneous cues (shadows visible through the closed eyelids, sounds generated by the experimenter, air movement during source placement, etc.) that may have allowed subjects to make judgments about the source location independently of the available audio information. In order to verify the insignificance of these cues, 100 trials were collected for each subject with the sound source disabled. The mean angular error in this condition was more than 50°, three times as large as when the sound source was enabled. The errors in

TABLE I. Mean angular errors. The mean errors and standard deviations for each of 27 stimulus regions were calculated separately for each of the four subjects, and then combined to generate the values in the table. The overall mean error at each distance is given in the last column, and the overall mean error at each azimuth is given in the last row. The standard errors are in parentheses. Trials where front–back confusions occurred have been excluded from these calculations.

Distance	Elevation		Azimuth Back < −120°		Azimuth Side −120° to −60°		Azimuth Front > −60°		Mean
Close < 25 cm	High	> 20°	27.0°	(1.3°)	16.2°	(0.5°)	20.6°	(0.8°)	19.3°
	Mid	−20° to 20°	18.6°	(0.5°)	16.3°	(0.4°)	19.3°	(0.9°)	
	Low	< −20°	20.4°	(0.9°)	15.6°	(0.6°)	19.6°	(0.8°)	
Medium 25–50 cm	High	> 20°	21.7°	(0.8°)	15.5°	(0.5°)	12.6°	(0.6°)	15.8°
	Mid	−20° to 20°	17.9°	(0.6°)	13.4°	(0.4°)	14.6°	(0.5°)	
	Low	< −20°	17.0°	(0.6°)	12.3°	(0.4°)	17.3°	(0.5°)	
Far > 50 cm	High	> 20°	22.9°	(1.1°)	14.2°	(0.7°)	12.6°	(0.8°)	15.7°
	Mid	−20° to 20°	20.0°	(0.8°)	13.3°	(0.4°)	13.7°	(0.6°)	
	Low	< −20°	14.8°	(0.5°)	13.4°	(0.5°)	16.1°	(0.6°)	
Mean			20.0°		14.5°		16.3°		16.9°

azimuth, elevation, and distance were also much larger than in the audio experiment. Thus, although subjects received some information about source location from extraneous cues, this information was insignificant compared to the information provided by the intended auditory stimulus.

The data collection was divided into 2-h sessions, each consisting of four or five 100-trial blocks separated by short breaks. A total of 2000 trials per subject were collected over four or five 2-h sessions. Subjects participated in several training sessions prior to formal data collection in order to familiarize themselves with the experimental procedure. They were not, however, given feedback during these practice sessions.

III. DIRECTIONAL LOCALIZATION RESULTS

A. Removal of front–back reversals

Front–back reversals are commonly reported in auditory localization. These reversals, which occur because the interaural level and time difference cues are approximately symmetric across the interaural axis of the head, cause listeners to perceive sounds at the mirror image of their true position across the frontal plane; a sound at 45° azimuth, for example, might be perceived at 135°. In this experiment, a relatively conservative definition was used to determine whether a reversal had occurred on a given trial: a reversal was declared only when the azimuth error was reduced at least 10° by reflecting the response across the frontal plane. According to this definition, front–back reversals occurred in approximately 10% of all trials in this experiment. In the analyses of directional localization performance, all trials where reversals occurred were omitted from the calculations. The distributions of front–back reversals across locations and across subjects are discussed later.

B. Angular error

The simplest measure of directional error is the angular error, which corresponds to the angle between the vector from the center of the head to the source location and the vector from the center of the head to the response location. The angular error is a comprehensive measure of directional accuracy that incorporates both azimuth and elevation errors and includes the effects of systematic response biases and of response variability. The mean angular errors were calculated for stimuli in each of 27 different regions of space representing three azimuth ranges, three elevation ranges, and three distances. The results (Table I) show that overall directional accuracy varies by more than a factor of 2 with location of the source. The largest errors occurred at locations above and behind the subject, especially when the source was close (mean error 27°), and the smallest errors occurred at relatively distant locations in front of and to the side of the subject.

When averaged across all distances and all elevations, the angular error was smallest when the source was to the side, and greatest when the source was behind the subject (Table I, bottom row). The increase in error at locations behind the subjects may result, in part, from the awkwardness of moving the pointer behind the body. The error also increased substantially as the source approached within 25 cm of the head, especially for source in front of and above the subject (right column), and the error increased slightly with increasing elevation. Overall, averaged across all subjects and all locations, the mean angular error was 16.9°.

C. Azimuth error

The raw azimuth data give an indication of both the precision of azimuth localization and of any major response biases. In Figs. 2 and 3, azimuth data are shown for two subjects: CLL, who experienced an exceptionally large number of front–back reversals, and KMY, whose responses were typical of the other two subjects used in the study. In each panel of the figure, the second-order polynomial line best fitting the stimulus–response data has been plotted. This line approximates the systematic biases for that subject in the indicated source region.

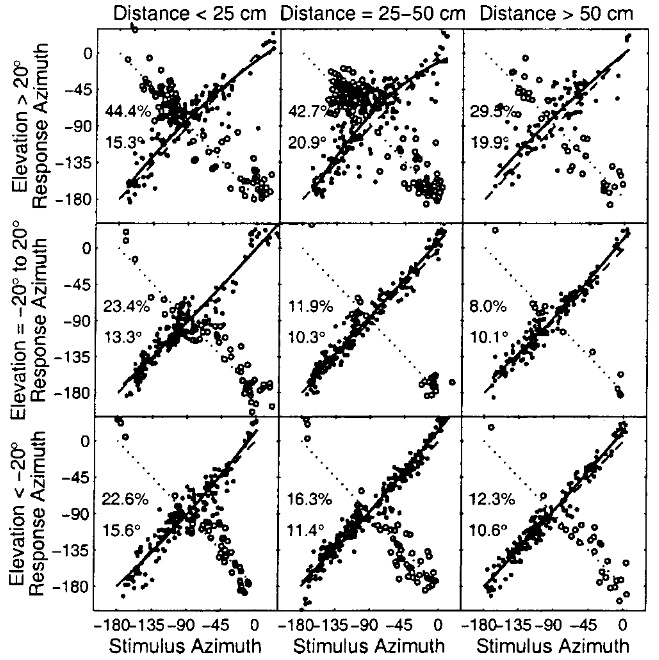

FIG. 2. Raw azimuth stimulus and response data for subject CLL. The data were sorted according to source distance into three regions: closer than 25 cm; from 25–50 cm; and farther than 50 cm. Similarly, the data were sorted by source elevation into three regions: above 20°; between −20° and 20°; and below −20°. Columns represent distance, increasing left to right, and rows represent elevation. The solid line is the second-order polynomial function of the stimulus location that best fits the response location. At the left of each panel are two numbers. The upper number is the percentage of front–back reversals (represented by open circles) in the region. The lower number is the BCRMS for all nonreversed responses in the panel (see the text). The dashed line represents ‘‘correct’’ responses, while the dotted line represents ‘‘perfect’’ reversals. Note that this subject exhibited an atypically large number of front–back reversals.

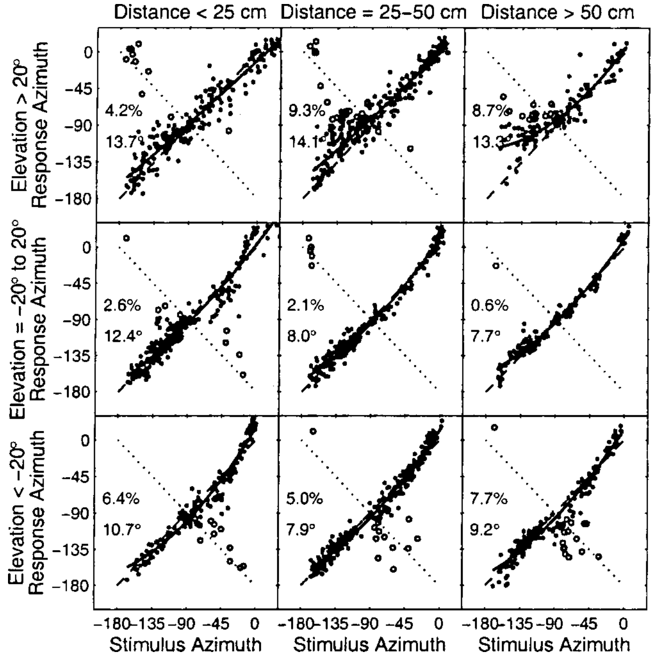

FIG. 3. Raw azimuth stimulus and response data for subject KMY. See Fig. 2 for details. This subject's data are similar to those of DSB and DTD.

TABLE II. Mean BCRMS azimuth error at three distances (close=<25 cm, medium=25–50 cm, far=>50 cm) and at three elevations (high=>20°, medium=−20° to 20°, low=>−20°). The data were calculated separately for each subject and averaged together to generate the figures in the table. Trials where front–back confusions occurred have been excluded from these calculations.

		Distance		
Elevation	Close	Medium	Far	Mean
High	14.2°	16.6°	14.8°	15.2°
Medium	12.2°	9.2°	9.5°	10.3°
Low	16.8°	10.4°	10.7°	12.6°
Mean	13.8°	12.1°	11.7°	12.6°

The biases change systematically with source location, and would confound a direct measure of response variability such as standard deviation. Therefore, a special measure of response variability that excludes the systematic response bias, called the bias-corrected root-mean-square (BCRMS) error, was calculated at nine elevation and distance locations for each subject. The BCRMS is simply rms error between the response location and the quadratic regression curve representing the best fit of the responses as a function of source azimuth. The BCRMS error is shown at the left of each panel in the figure, and the mean BCRMS azimuth errors averaged across the four subjects are shown in Table II. It should be noted that all four subjects performed quite similarly in terms of the BCRMS error, with the exception of subject CLL at high elevations.

The BCRMS error in azimuth was significantly larger at high elevations than at low or middle elevations for each of the four subjects (F-test, $p<0.002$). Note that this increase in error is at least in part a result of the increased sensitivity of azimuth at high elevations in the polar coordinate system. The same effect is not as pronounced at low elevations because more trials were collected at very high elevations (>45°) than at very low elevations (<−45°).

The BCRMS error was not strongly dependent on distance. The overall BCRMS error (averaged across all three elevations) was significantly larger at the closest source distances (<25 cm) than at the greatest source distances (>50 cm) for only two of the four subjects (KMY and CLL). Subject DSB actually exhibited significantly larger errors at intermediate distances (25–50 cm) than at close distances (<25 cm) (F-test, $p<0.02$).

D. Distribution of front-back reversals

The top number on the left side of each panel in Figs. 2 and 3 indicates the percentage of trials where front–back reversals occurred in each location. Figure 4 summarizes the relationship between the percentage of front–back reversals and the source location. Four important observations can be made from the reversal data.

(i) Subject CLL has far more reversals than any other subject, and dominates the mean reversal percentages across subjects. In certain locations, CLL reverses the majority of trials.

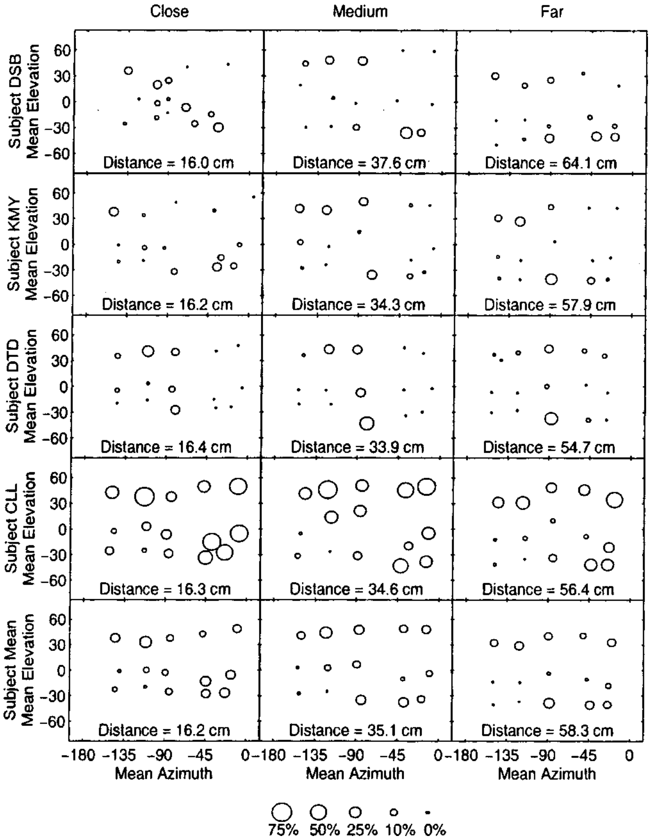

FIG. 4. Spatial distribution of front–back reversals. First, the data were sorted into three nonoverlapping distance bins, then each distance bin was sorted into eight overlapping azimuth bins, and finally each azimuth bin was sorted into three nonoverlapping elevation bins. The number of reversals in each bin is shown as a function of mean location for each individual subject and averaged across all four subjects, where a reversal is defined as any trial where the response was at least 10° closer to the mirror image of the source location across the frontal plane than to the actual source location (see the text). For clarity, only five bins are shown in azimuth. The three bins to the side and the rear are nonoverlapping, while the two bins near 0° are overlapping. The percentage reversals at each location are shown by the size of the circle, according to the code shown at the bottom of the figure. The distances at the bottom of each panel represent the mean distance of all the data points in that region.

(ii) Only CLL shows a significant distance dependence in the percentage of front–back reversals. CLL reversed a significantly larger percentage of trials at close and medium distances (<50 cm) than at far distances (>50 cm) (one-tailed t-test, $p<0.005$).

(iii) Relatively few reversals occur at middle elevations. One-tailed t-tests ($\alpha=0.005$) indicate that all four subjects reversed a significantly larger percentage of trials at high elevations ($>20°$) than at middle elevations, and that three subjects (DSB, KMY, and DTD) reversed a significantly larger percentage of trials at low elevations ($<-20°$) than at middle elevations.

(iv) In the rear hemisphere, the vast majority of reversals occurs at high elevations. In contrast, almost all reversals in the front hemisphere for subjects DSB and KMY occur at low elevations. The variations in the placement of reversals across subjects is not surprising, since the subjects must essentially make an arbitrary decision about the true location of the source whenever they are unsure about the actual hemisphere of the source.

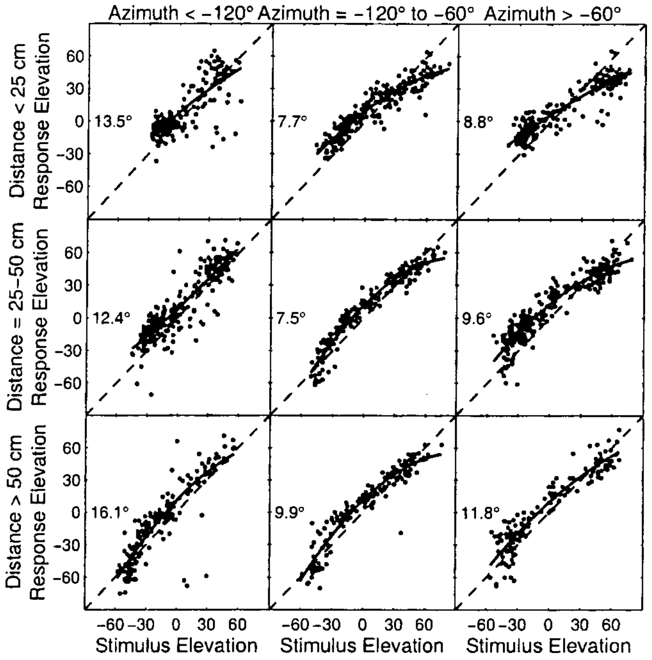

FIG. 5. The nine panels show raw elevation stimulus and response locations for subject KMY, a typical subject in the experiment. Azimuths were divided into regions less than $-120°$, from $-120°$ to $-60°$, and greater than $-60°$. Distances were divided into regions less than 25 cm, from 25 to 50 cm, and greater than 50 cm. A dashed line represents correct responses. The BCRMS elevation error is shown at the left side of each panel, and the solid line represents the best second-order polynomial fit of the stimulus data to the response locations. Note that the stimuli range from approximately $-45°$ to 80° in elevation. The data are limited at low elevations because the subject's torso and the chin rest prevented placement at some source locations. For example, low elevations are particularly truncated at close distances behind the subject where the neck and back prevented placement at low elevations.

E. Elevation error

The raw elevation data for a typical subject are shown in Fig. 5 in a format similar to the one used for the raw azimuth data. These raw data are typical of the other subjects in the experiment. The overall BCRMS elevation errors, averaged across the four subjects, are provided in Table III. Several important observations can be made from these data:

TABLE III. Mean BCRMS elevation error at three distances (close $=<25$ cm, medium$=25$–50 cm, far$=>50$ cm) and at three azimuths (rear$=<-120°$, side$=-120°$ to $-60°$, front$=>-60°$). The data were calculated separately for each subject and averaged together to produce the value shown in the table.

	Azimuth			
Distance	Rear	Side	Front	Mean
Close	14.6°	9.5°	11.2°	11.7°
Medium	13.0°	8.6°	10.0°	10.5°
Far	14.7°	9.3°	11.3°	11.8°
Mean	14.1°	9.1°	10.8°	11.3°

(i) The elevation responses tended to show more dramatic biases than the azimuth data. In the data shown for KMY (Fig. 5), the quadratic line best fitting the data is typically concave down, in part because the subject tended to underestimate the elevation of high sources.

(ii) The overall BCRMS error in elevation, which attempts to eliminate the effects of bias, was comparable to that for azimuth (11.3° vs 12.6°). Note that the azimuth figure is inflated somewhat by its increased sensitivity at high and low elevations in the polar coordinate system.

(iii) Elevation localization performance was best to the side, and worst to the rear. An F-test on the BCRMS errors reveals that each of the four subjects was significantly more accurate in front than in back, and most accurate to the side ($p<0.01$ level).

(iv) Elevation performance did not depend on distance in a consistent way. Two of the subjects (DSB and KMY) had significantly lower errors at distances less than 25 cm than at distances greater than 25 cm, and the other two subjects had significantly lower errors at distances greater than 25 cm than at distances closer than 25 cm (F-test, $p<0.005$).

F. Response biases

To this point, the primary focus has been the variability of subject responses in the form of the bias-corrected unsigned error. Systematic directional biases are also of considerable interest. Figure 6 shows the response bias (mean uncorrected signed error) in azimuth and elevation as a function of source location. Note that the directional biases are generally invariant to source distance. Although the directional biases differ substantially from subject to subject, the general pattern of biases for each of the subjects is consistent across the three distance bins. Subject DSB, for example, has a bias up and toward the front for sources behind and above the head at all distances, while CLL is generally biased down and toward the front at high elevations. It appears that directional response biases are roughly independent of distance.

G. Discussion

In order to put these results into context, it is useful to compare them to previous estimates of directional localization ability available in the literature. Although no data are available on proximal-region localization, our results at distances greater than 50 cm can be compared to previous data collected 1 m or farther from the subject. Two studies which have evaluated directional localization (position identification) are Wightman and Kistler (1989) and Makous and Middlebrooks (1990).

The overall angular errors measured in this study were substantially smaller than those measured by Wightman and Kistler (15.2° at distances greater than 50 cm in this study, compared to 21.1° measured by Wightman and Kistler). This discrepancy most likely results from the increased stimulus uncertainty in the Wightman and Kistler study (they used a scrambled stimulus spectrum rather than the fixed stimulus spectrum in this study).

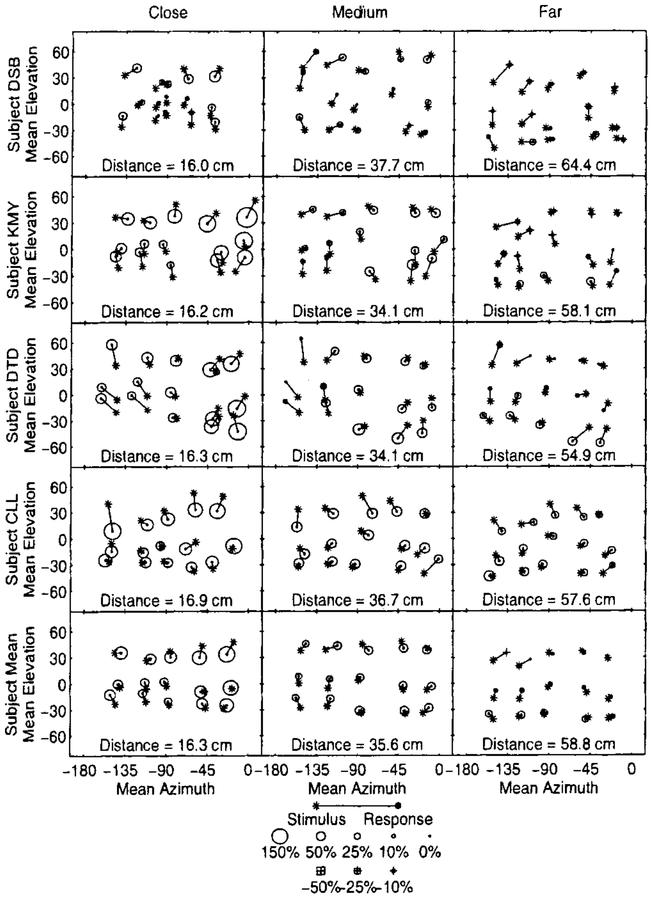

FIG. 6. Response bias size and direction as a function of source location. Details are similar to Fig. 4. The asterisk is the mean stimulus location, while the dot is the mean response location. The circles indicate that the subject overestimated distance (see the legend), while the crosses surrounded by squares indicate an underestimate of distance.

In contrast, the standard deviations in azimuth and elevation measured in this study were substantially larger than those measured by Makous and Middlebrooks. For example, their results indicate a standard deviation of only 1.9° in azimuth and 3.3° in elevation for sources directly in front of the listener (0° azimuth and −5° in elevation), compared to standard deviations (BCRMS) of approximately 6° in azimuth and 8° in elevation for sources in front of the listener in this study.

All three studies indicate that directional localization judgments are least accurate when the source is located above and behind the head. Since all three studies report poorest performance in this region, using three different response methods, it is likely that there are some perceptual problems in localizing sound behind and above the head. However, the reasons for poor perception in this region are not obvious.

Finally, more front–back reversals occurred in this experiment than in the two earlier studies. If front–back confusions are counted whenever the stimulus and response locations are on opposite sides of the frontal plane, front–back confusions occurred in 13% of all trials in this experiment at distances greater than 50 cm, compared to 6% of all trials in the other two experiments.

The comparison of the data at distances greater than 50 cm with previous data is useful for establishing a baseline for comparison with the results at closer distances. Of primary importance in this study, however, is the effect of an extremely close source on directional localization ability. The angular error increases significantly as distance decreases (Table I), but this increase is at least in part a result of larger response biases when the source is close, rather than larger response variability. Response variability, measured by the BCRMS errors in azimuth and elevation, did not vary consistently with distance. The azimuth error was significantly larger at close distances (<25 cm) than at far distances (>50 cm) for only two of the four subjects. The elevation bias-corrected error was significantly larger at close distances than at far distances for two subjects, but significantly larger at far distances than at close distances for the other two subjects. There is also some reason to believe that experimental error is slightly greater for very close sources than for more distant sources. At locations very close to the head, direction is very sensitive to small displacement errors. At 12 cm, for example, a 1-cm error in the subject response, or in the measurement of the stimulus and response locations, can cause a directional error of nearly 5°. When the increased error sensitivity of the response method for very near sources is weighed against the relatively minor decrease in performance at close distances, it appears that source distance has, at most, a marginal effect on directional accuracy in the proximal region.

Front–back reversals increased slightly at close distances for all four subjects, but only one subject (CLL) reversed a significantly larger percentage of trials at close distances than at far distances. CLL appeared to be a ''poor localizer'' in general, in that he experienced substantially more front–back confusions than the other subjects, even at the greatest distances tested. Although data are available from only one subject, it may be the case that the localization problems of poor localizers are exacerbated when the source is very near the head, but that normal localizers may be unaffected by sources very close to the head.

IV. DISTANCE LOCALIZATION

A. Results

One of the primary motivations for this experiment was an examination of the accuracy of auditory depth perception for nearby sources. The raw data for proximal-region distance perception for a typical subject are provided in Fig. 7. There are three striking features in these data:

(i) The magnitudes of the distance errors tend to increase with distance. For this reason, the stimulus-response curves in distance have been plotted on a log–log graph rather than a linear graph.

(ii) The distance errors are greater near the median plane [azimuths in back ($<-120°$) and in front ($>-60°$)] than at more lateral locations.

(iii) The distance errors are greater at high elevations ($>20°$) than at middle and low elevations.

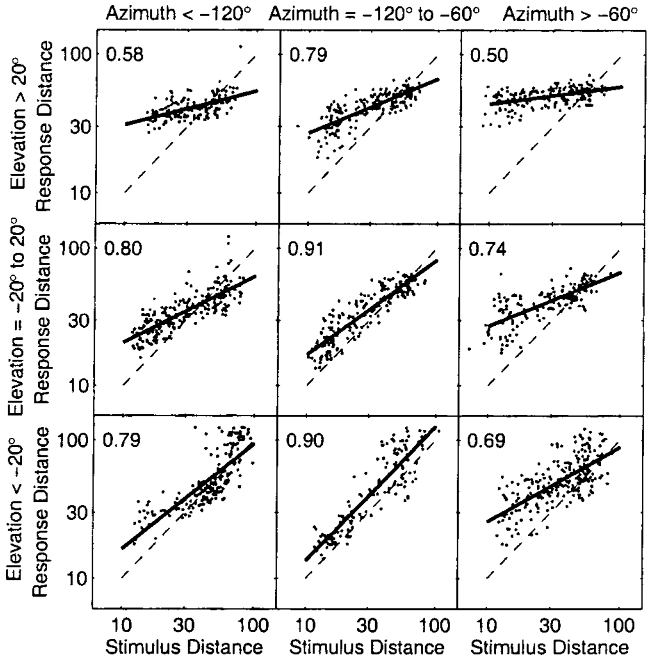

FIG. 7. Raw distance data for subject KMY. The columns represent different azimuths, and the rows represent different elevations. The data are plotted on a log–log scale representing the distance from the center of the head (in cm). Note that in a typical subject the tip of the nose is approximately 10 cm from the center of the head, and the ears are approximately 7 cm from the center of the head. In some cases, the sound source was within 1 cm of the surface of the head. The correlation coefficient of the log stimulus distance and log response distance is shown at the top left of each panel. The dashed line indicates correct responses, and the solid line is the least-squared linear fit of the log–log data.

An overall summary of distance performance collapsed over all elevations is the RMS percentage distance error (Fig. 8). This measure indicates that the overall average error in distance is approximately 30%–40% across all azimuth locations.

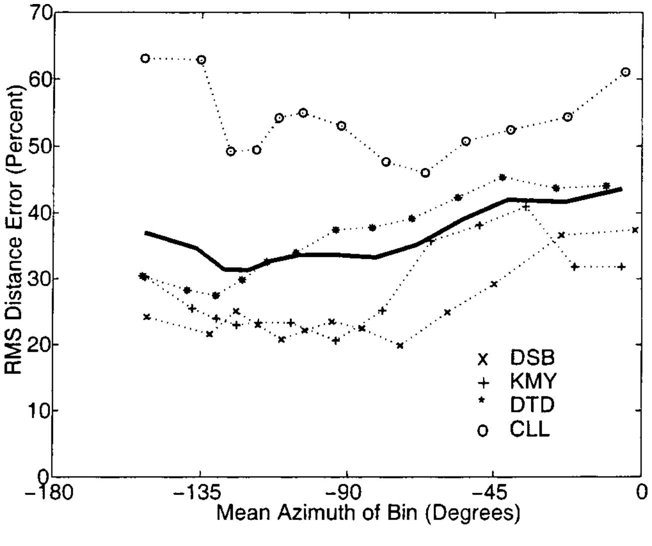

FIG. 8. rms percent distance error as a function of azimuth. Each subject's responses were sorted by azimuth into 13 overlapping bins containing 14% of the total number of trials. Then, the rms percentage distance error (uncorrected for bias) calculated in each bin was plotted as a function of the mean azimuth location in each of the 13 bins. The solid line shows the average of the percent rms errors calculated for each of the four subjects.

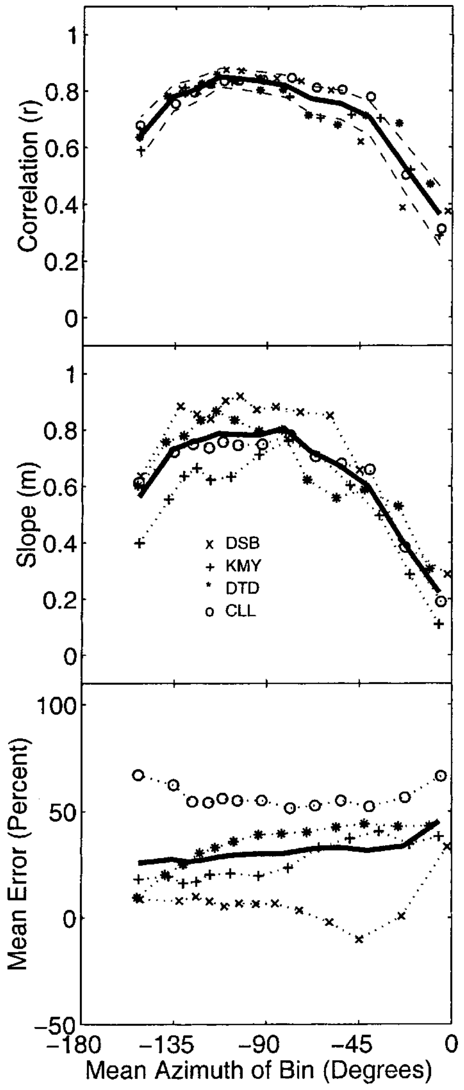

FIG. 9. Correlation, slope, and overall bias of the log distance responses as a function of azimuth. As in Fig. 8, the subject responses were sorted by azimuth into 13 overlapping bins, each containing 14% of the total number of trials, and the correlation coefficient (top panel), the slope of the linear regression line (middle panel), and the overall mean signed percentage error in distance (bottom panel) were calculated separately in each bin and plotted as a function of the mean azimuth of each bin. The solid lines represent the mean values across the four subjects. In the top panel, a Fisher transformation was used to average the correlation coefficients across the four subjects and to compute the 95% confidence interval (dashed lines).

The overall distance errors can be divided into three components: an overall distance-independent bias representing a general tendency to overestimate or underestimate distance (the mean percentage error in distance); a bias in ‘‘scaling’’ representing a tendency to compress or expand the responses in distance (represented by the slope of the least-squared linear fit of the data); and an error term related to the variability of the responses for a particular stimulus location (represented by the spread of responses around the least-squared fit line).

Figure 9 illustrates the bias and uncertainty components of the distance error separately. The top panel shows the correlation coefficient of the log stimulus and response distances as a function of source azimuth. The correlation coefficient is related to the bias-corrected variability in the responses and can be viewed as the degree to which the source distance can be determined from a linear function of the log response distance.[2] Note that the correlation coefficient is significantly greater for sources at lateral locations than for sources at medial locations, and that this pattern is consistent across each of the four subjects. Also note that the data are roughly symmetric in the front and rear hemispheres, but that there are no data points behind −150° in azimuth.

The middle panel shows the slope of the line best fitting the log stimulus data to the log response data at each azimuth location. This slope is a measure of the scaling bias in the responses: a slope of less than 1 indicates that the responses varied over a narrower range of distances than the stimulus locations (a compression in the responses). Like the correlation coefficient, the slope is relatively high at lateral locations and relatively low at medial locations. This indicates that the subject's responses are more sensitive to the true source location at lateral locations, which accounts for the increased correlation coefficient at these locations. Note that, even at lateral locations, the slope is less than 1 for all subjects, indicating a general tendency to compress distance responses.

The bottom panel shows the overall percentage error in distance, which indicates any distance-independent biases in the subject's responses. This is the only performance measure that shows a substantial difference across the four subjects. In particular, subject CLL exhibits a strong tendency to overestimate distance (in excess of 50%). The other subjects also generally overestimated distance, but to a lesser extent. The overall pattern of this percentage error as a function of azimuth is quite similar to the rms percentage error in Fig. 8 for each of the four subjects, indicating that rms percentage error is dominated by overall bias and that it is only a weak indicator of response precision.

The degree to which the correlation coefficient and the slope of the linear regression line represent the characteristics of the subject responses can be illustrated by a comparison of the raw stimulus–response data in two azimuth bins, one near the median plane and one near the interaural axis. The results for subject DSB (Fig. 10), which are typical of those for the other subjects, confirm that the primary reason for the decrease in correlation in the median plane is that the slope of the stimulus–response line is much lower. In fact, almost all of the responses in the front bin are grouped around 60 cm, independent of the actual stimulus location. A similar pattern occurs in the data from all four subjects.

The correlation coefficient and the slope of the regression line also indicate that distance localization performance is substantially worse at high elevations (above 20°) than at middle and low elevations. The correlation coefficient between the log stimulus and response distances, calculated separately for each subject in each of 13 azimuth bins and averaged using the Fisher transformation (Devore, 1991), decreases from 0.81 at locations below 20° in elevation to 0.65 at locations above 20°. Similarly, the average slope of the responses decreases from 0.76 at low and middle elevations to 0.42 at high elevations.

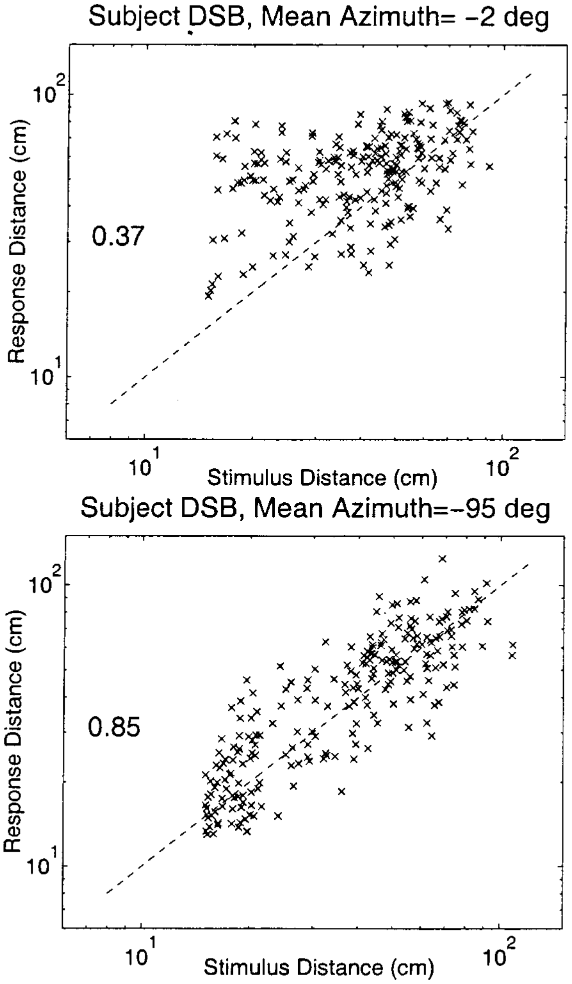

FIG. 10. Raw distance data for subject DSB in front and to the side. These plots show the data for subject DSB in the 1st and 7th azimuth bins used to calculate the results in Fig. 9. In front (top panel), the responses tend to be clustered around 60 cm independent of the source location, while to the side (bottom panel) the response distance varies systematically with stimulus distance.

B. Discussion

It is difficult to compare distance localization in this experiment to previous results. Few studies have directly examined auditory distance perception as a function of direction, and even fewer have examined distance perception for nearby sources. We know of only two studies which have directly examined proximal-region distance perception. Ashmead, LeRoy, and Odom (1990) found that listeners were able to perceive relatively large (>16%) changes in the distance of a nearby sound source directly in front of them even when the amplitude of the source was manipulated to eliminate loudness-based distance cues. This indicates that some distance information (perhaps spectral) is available even in the median plane, where binaural distance cues are minimal.

Simpson and Stanton (1973) performed an experiment specifically designed to look for binaural distance cues for close sources. Subjects were asked to estimate the distance of a sound source placed directly in front of the listener at one of five locations ranging from 30 cm to 2.7 m. Some of the subjects used a fixed head position during the experiment, some were allowed to turn their heads, and some were required to move their heads. Simpson and Stanton found that head motion had no significant effect on distance perception. Since the results of the current experiment indicate that distance accuracy is substantially better for lateral sources than for medial sources, it is surprising that Simpson and Stanton's subjects were not able to judge distance more accurately when they were allowed to turn their heads away from the sound source. Amplitude and reverberation in the Simpson and Stanton study may account for the discrepancy. The amplitude of the source was fixed during their experiment, and their subjects were seated in the corner of a sound-treated listening booth, with their heads only 25 cm from either wall. Thus, it is likely that their subjects were able to use amplitude and reverberation cues to judge distance, and these cues may have dominated the binaural distance cues in their experiments.

In contrast to the Simpson and Stanton paper, two studies of distal-region localization have indicated that distance perception is better for sources along the interaural axis than for sources in the median plane when the amplitude of the source is randomized. Holt and Thurlow (1969) found that subjects could accurately determine the relative distances of the sound sources when they were lined up with the interaural axis (rank-order correlation of 0.93), but not when the sources were directly in front of the subject. Gardner (1969) informally reported a similar result. The relationship between azimuthal position and distance localization accuracy found in these earlier studies is in agreement with the results of this experiment, but we cannot explain why subjects were able to perform so well in the distal region where binaural distance cues are largely absent.

Other than the observations of Holt and Thurlow, and Gardner, no previous studies have indicated that distance perception is better for lateral sources than medial sources at close distances. Furthermore, the strong correlations found in this study (as large as 0.85 for sources near 90°) indicate that distance perception is reasonably accurate in this region. Performance in this region appears to exceed that indicated in any previous distance study where overall level cues were unavailable, which is especially noteworthy considering the additional requirements of simultaneously determining source azimuth, elevation, and distance in this experiment.

V. COMPARISON OF RESULTS TO PROXIMAL-REGION HRTF MEASUREMENTS

By comparing the results of this psychoacoustic experiment with previously measured HRTFs in the proximal region, we can gain insights into the mechanisms of proximal-region localization. The features of the proximal-region HRTFs, along with previous results from distal-region localization experiments, can explain the relatively weak distance dependence of directional localization, as well as the relatively accurate distance judgments for lateral sources.

Although three of the four subjects were slightly less accurate at azimuthal localization when the sound source was close to the head, the decrease in performance was relatively minor. Similar horizontal localization performance in the proximal and distal regions may indicate that low-frequency ITDs dominate azimuth judgments in the proximal region as they have been shown to do in the distal region. Previous work by Wightman and Kistler (1992) has shown that ITDs tend to dominate azimuthal localization when the stimulus contains low-frequency energy. Note, however, that Wightman and Kistler's experiments manipulated the time delay in HRTFs measured in the distal region. The low-frequency time delay clearly dominates perception with the distal-region HRTFs, where the ILD was significant only at high frequencies. When the source is in the proximal region, however, the ILD can be large even at low frequencies, and the Wightman and Kistler data provide no direct evidence that the ITD dominates the influence of low-frequency ILD on azimuth perception. The absence of a strong lateral azimuth bias for nearby sources provides some indirect evidence that ITD dominance extends into the proximal region. In the proximal region, an increase in ILD could result either from a source moving closer to the head or from a source moving away from the median plane. If azimuth judgments were based on ILD, one might expect listeners to confuse the distance and direction of the source in the proximal region, resulting in a lateral bias for nearby sources. There is, however, no indication of such a bias in the data. The lack of lateral directional biases for nearby sources, coupled with comparable directional accuracy in the proximal and distal regions, indicates that proximal-region azimuth perception is most likely based on ITDs which are essentially independent of source distance.

The psychoacoustic results indicate that elevation perception does not depend on distance in a systematic way. Two subjects performed slightly better in elevation when the source was distant, and two performed better when the source was close. This is consistent with the observation (Brungart and Rabinowitz, 1999) that the high-frequency features of the HRTF which change systematically with elevation are relatively independent of distance.

The distance perception abilities of our subjects, and in particular their ability to make unbiased, accurate distance judgments about lateral sources and their inability to make distance judgments about medial sources, suggest that the variations in the ILD with angle and distance provide a useful binaural proximal-region distance cue. In the distal region, the ILD varies only with direction. In the proximal region, the ILD increases as the source approaches the head. The usefulness of this increase as a distance cue is related to the range over which the ILD varies in a particular direction. The range of possible ILDs is largest when the source is to the side, and decreases to zero in the median plane. This pattern mirrors the distance performance by the subjects, which was also best for lateral sources and worst in the median plane. In fact, the only major discrepancy between distance localization accuracy and the range of possible ILD values is that localization performance appears to plateau in the region from $-45°$ to $-135°$, while the span of ILDs increases systematically up to $-90°$. This could be explained by the well-known range effect in stimulus identification experiments, which causes sensitivity to changes in a stimulus to decrease when the range of possible values increases (Durlach and Braida, 1969; Koehnke and Durlach, 1989). The range effect, which is based on memory noise rather than sensory noise, could explain the saturation in performance seen in this experiment. Note that ILD-based distance cues could also explain the decrease in performance at high elevations (and the more rapid decrease in performance away from $-90°$), since the ILD is smaller at high elevations than in the horizontal plane.

VI. CONCLUSIONS

The general results of these experiments can be summarized as follows:

(i) The angular error, which includes the effects of response bias and response variability, increases as the source approaches the head, particularly in front of and behind the listener.
(ii) The bias-corrected rms azimuth error is greatest at high elevations and generally increases slightly at close distances.
(iii) The bias-corrected rms elevation error is lowest for lateral sources and greatest behind the listener. It does not vary consistently with distance.
(iv) Distance perception is most accurate for lateral sources and least accurate near the median plane. For lateral sources, distance judgments were highly correlated with actual source position ($r>0.85$), and were relatively unbiased; in the median plane, the correlations were low ($r<0.4$). The results generally indicate better distance perception in the proximal region than in previously reported studies involving sources of unknown strength in anechoic conditions.
(v) The psychoacoustic results are consistent with previously measured HRTFs in the proximal region, which indicate that ILD varies with distance in the proximal region while ITDs are roughly independent of distance. In particular, the results support the hypothesis that ILDs are an important binaural distance cue in the proximal region.

It appears that directional localization is modestly degraded when sources are close to the head, but that distance perception may be substantially improved, at least for sources away from the median plane, by the availability of binaural distance cues in the proximal region. Additional experiments are necessary to fully understand the mechanisms of proximal-region localization. The next paper in this series will look at the effects of different stimuli (e.g., bandlimited, monaural, or fixed amplitude) on proximal-region localization.

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[1] Note that these regions have sometimes been referred to as the ''near field'' and the ''far field.'' Since these terms have very specific meanings in physical acoustics, we have introduced new terminology to eliminate any ambiguities.

[2] The use of the correlation coefficient requires an approximately linear relationship between the two variables. An examination of the raw data indicates that this approximately linear relationship exists between the log of the stimulus distance and the log of the response distance for each of the four subjects.

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