Minimum audible angle thresholds for sources varying in both elevation and azimuth

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Minimum audible angle (MAA) thresholds were obtained for four subjects in a two-alternative, forced-choice, three up/one down, adaptive paradigm as a function of the orientation of the array of sources. With sources distributed on the horizontal plane, the mean MAA threshold was 0.97°. With the sources distributed on the vertical plane (array rotated 90°), the mean MAA threshold was 3.65°. Performance in both conditions was well in line with previous experiments of this type. Tests were also conducted with sources distributed on oblique planes. As the array was rotated from 10°–60° from the horizontal plane, relatively little change in the MAA threshold was observed; the mean MAA thresholds ranged from 0.78° to 1.06°. Only when the array was nearly vertical (80°) was there any appreciable loss in spatial resolution; the MAA threshold had increased to 1.8°. The relevance of these results to research on auditory localization under natural listening conditions, especially in the presence of head movements, is also discussed.

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INTRODUCTION

Thurlow *et al.* (1967) reported the results of an experiment in which blindfolded subjects were allowed to move their heads while attempting to identify the location of a sound source. As illustrated in Fig. 1, they observed three classes of movements: rotation of the head about the central vertical axis (rotational movements); rotation of the head about the aural axis (up/down or tipping movements); and movements that result in the head being cocked to one side (pivoting movements). Observations made in our laboratory over the last several years appear to be in good agreement with those reported by Thurlow and his co-workers. Head movements, when they occur, most typically involve some combination of these movements. The most common movement that we have encountered is a concurrent tipping-rotational adjustment of the head. While large tipping movements are most evident for sources located off the horizontal plane, rotations about the aural axis in excess of 10° can readily be observed even for events initially located at ear level. We found the prevalence of this tipping-rotational motion particularly curious since it suggests that listeners must frequently assess *simultaneous changes in the relative azimuth and elevation of a sound source*, at least when head movements are involved.[1]

Sound localization performance has been extensively examined for events located on the forward region of the subject's horizontal plane. In general, spatial acuity appears to be particularly good for broad bandwidth stimuli presented from sources located near 0° azimuth. Under optimal conditions, MAA thresholds for individual subjects may be less than one degree (Perrott and Pacheco, 1989). Similar estimates of auditory spatial acuity have also been obtained in tasks requiring subjects to identify the direction of travel of a moving sound source when broad bandwidth stimuli have been employed (Perrott and Marlborough, 1989). This latter observation is important, considering that changes in the relative position of a sound source created by movements of the head would be identical to the changes obtained when the source, rather than the subject, was moving.

Events presented on the vertical plane do not appear to be as readily resolved, even when broad bandwidth stimuli are employed. Minimum audible angle thresholds obtained for changes in elevation are generally two to four times larger than those observed on the horizontal plane (e.g., Wettschureck, 1973; Morrongiello and Rocca, 1987). There are currently no data available on the ability to detect "motion" of a sound source traveling in this plane.

Minimum audible angle thresholds have not been reported for sources distributed along an "oblique" plane. Given our interest in naturally occurring head movements where concurrent changes in the relative elevation and azimuth of a sound source seem to be a common occurrence, we decided to give this latter problem some attention.

I. METHOD

A. Subjects

Two university students, who were paid to participate in this experiment, and the authors DRP and KS served as subjects.

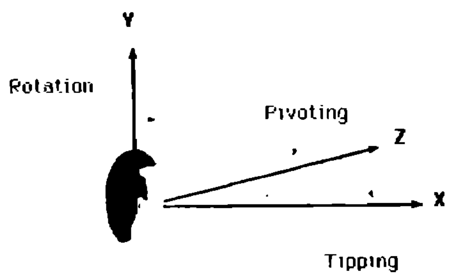

FIG. 1. Three types of movements identified by Thurlow *et al.* (1967): rotation, tipping, and pivoting.

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B. Apparatus

The stimulus consisted of a 50-ms, 400-Hz click train presented at 52 dB (A-weighting) from one of thirty 5.7-cm mid-range loudspeakers. The loudspeakers were mounted on a boom that could be rotated through a 90° arc. This boom-mounted speaker array was located in a large test chamber (9.1×12.2×2.1 m). All surfaces of this chamber had been covered with 10.2-cm acoustic foam wedges (@ Sonex) to minimize sound reflections.

C. Procedure

The subject was seated 716 cm from the speaker array. Head position was fixed by a chin clamp during testing. At the beginning of each trial, one of the 10 speakers located in the middle of the array was selected as the referent. A 50-ms click train was emitted from this referent source. After a 500-ms interstimulus interval, a second 50-ms click train was presented from another source on the speaker array. Feedback was presented immediately if the subject correctly identified the position of the second source relative to the location of the referent source on that trial. On the next trial, the referent source was again randomly selected from one of the 10 centrally located loudspeakers on the array. In effect, the location of the referent was "jittered" randomly from trial to trial. With the boom in the horizontal orientation, the minimum angular separation between speakers was 0.46° azimuth. Thus the referent event was always located within 2.3° of 0° azimuth and elevation.[2]

Across sessions, subjects were tested with the speaker array in the following configurations: 0° (horizontal orientation), 10°, 20°, 30°, 40°, 45°, 50°, 60°, 70°, 80°, and 90° (vertical orientation). Figure 2 illustrates the situation encountered by the subject when the array was rotated. The separation of the speakers, in degrees azimuth and elevation, is presented in Table I as a function of the orientation of the array. Note that the minimum change in azimuth is 0° for the speakers presented in the vertical orientation, and the minimum change in elevation is 0° for speakers arrayed horizontally. Thus the angular distance between sources (in azimuth and elevation) varies in a substantial manner as a function of the orientation of the array. All subjects completed at least two sessions at each speaker array orientation.

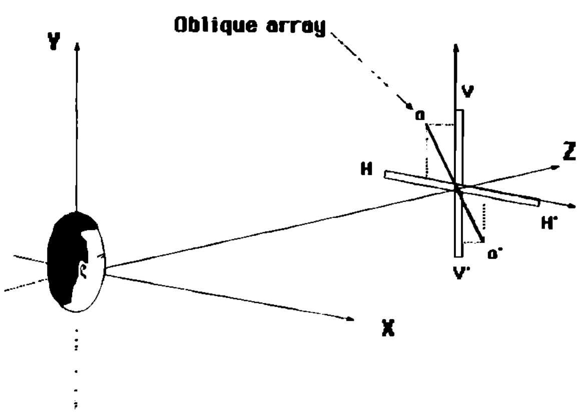

FIG. 2. Line OO' illustrates the situation with the array rotated approximately 60° from the horizontal. Note that the vertical (broken) lines extending from points O and O' intersect line HH' well inside its terminal limits. In effect, the angular distance in azimuth for line OO' is only half of that available when the same array is not rotated.

TABLE I. The speaker array was located 716 cm from the subject. The distance between the speakers was 5.7 cm. For the array oriented horizontally, the angular separation in degrees azimuth was 0.457° and the angular separation in elevation was 0°. This table lists the separation of the speakers in degrees azimuth and degrees elevation for the various array orientations employed in the current study.

Array orientation	Angular separation of the sources	
Slope in degrees	Degrees azimuth	Degrees elevation
0	0.457	0.000
10	0.450	0.079
20	0.429	0.156
30	0.395	0.228
40	0.350	0.293
45	0.320	0.320
50	0.293	0.350
60	0.228	0.395
70	0.156	0.429
80	0.079	0.450
90	0.000	0.457

A single-interval, two-alternative, forced-choice adaptive procedure was used. With the sources arrayed in the horizontal configuration, the subjects were asked to indicate whether the second event was to the right or left of the referent speaker on that trial. With the array rotated 90°, the subjects were required to indicate whether the second event was above or below the referent. For all oblique orientations, the sources varied in both elevation and azimuth. Under these conditions, the subject indicated whether the second event was above and to the left or below and to the right of the first. A single incorrect response resulted in an increase of 5.7 cm between the referent and comparison source to be employed on the next trial. Three successive correct responses resulted in an equivalent decrease in the inter-source distance. Fifty reversals in direction were obtained within a session, with the last 30 reversals being used to calculate one estimate of the MAA threshold (a 79.6% correct response level was used). The MAA threshold for each subject, at each orientation of the array, was based on the average of thresholds obtained over two to three sessions.

II. RESULTS

Figure 3 presents the MAA thresholds as a function of the orientation of the array. The thresholds obtained with the array in the horizontal and vertical configurations agree quite well with the results of earlier reports (0.97° and 3.65°, respectively). The rotation of the array by as much as 60° from the horizontal appears to have had essentially no impact on localization resolution. While the thresholds are moderately elevated with the array at 70° (1.24°), the first statistically significant decline in performance over that observed with the array in the horizontal configuration was evident only when the array had been rotated to within 10° of the vertical plane. Auditory spatial resolution thus appears to be essentially constant for a broad range of stimulus con-

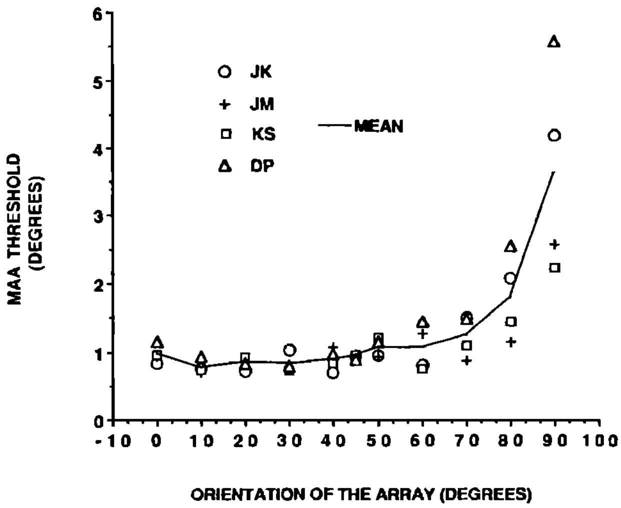

FIG. 3. MAA thresholds in degrees for four subjects are plotted as a function of the orientation of the array.

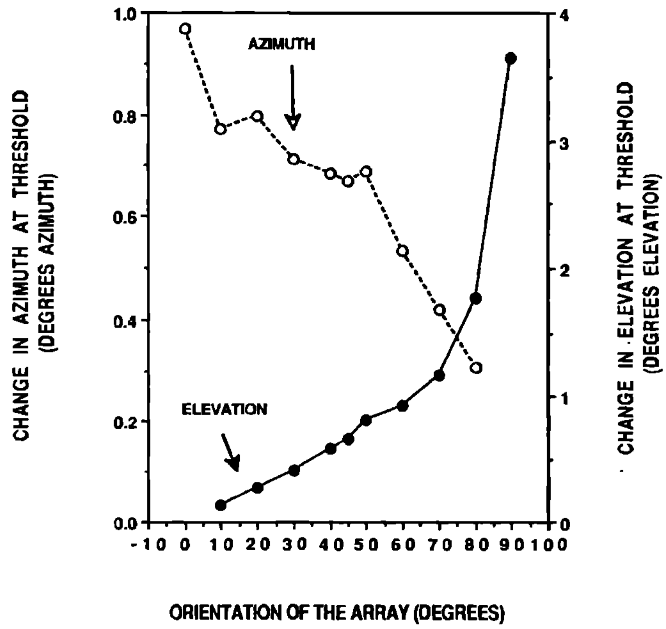

FIG. 4. The open symbols indicate the minimum azimuth difference required to perform the MAA task. The closed symbols indicate the minimum elevation difference required. For array orientations between 10°–80°, these differences in azimuth and elevation were concurrently available.

figurations (approximately 1.0°) when broad bandwidth stimuli are employed.

III. DISCUSSION

The idea that the auditory system may have constant acuity for events dispersed in space (with the exception being events falling nearly exactly on the vertical plane) makes sense in a complex, three-dimensional world. It is extremely unlikely, for example, for a listener to encounter events that are arrayed exactly on the horizontal plane. It is also clear from these results that changes in the relative position of a sound source generated by concurrent tipping and rotational movements of the subject's head, as described earlier, would *not* result in any appreciable cost in spatial resolution. In fact, the substantial improvement in resolution seen for sources located on the vertical plane when a small variation in azimuth is also available suggests that the pivoting and tipping head movements observed during the course of a rotational movement about the central vertical axis may be of immediate value to the listener.

As noted earlier (see Table I), the location of sources distributed on an oblique plane varies in both elevation and azimuth. In our task, the second source was either to the left and above the first or it was to the right and below. As the array was rotated from the horizontal to a more vertical configuration, the relative distance in azimuth between the sources decreased and the relative distance in elevation increased. Thus, when a subject is able to resolve the relative location of a sound source under these conditions, he may be using the lateral displacement (azimuth), the vertical displacement (elevation), or both. Figure 4 presents the MAA threshold data broken down into the azimuth and elevation differences that were available at threshold to the subject across the various orientations examined in the present study. The function plotted with open symbols indicates the available difference in azimuth; a difference in azimuth of 0.97° was required with the array in the horizontal configuration (i.e., no change in elevation was present), but only a 0.31° difference in azimuth was available with the array rotated 80°. The function plotted with filled symbols indicates the differences in elevation that were available. Again, the maximum change in elevation (3.65°) is observed when the array is in the vertical configuration (i.e., no change in azimuth was present) and the minimum is 0.14° for the array rotated to only 10° above the horizontal plane.

For array orientations between 0°–60°, where MAA thresholds appear to be constant, the azimuth difference available at threshold systematically decreases as a direct function of the displacement of the array from the horizontal plane. With the array rotated 60°, the lateral displacement of the source at threshold was only 0.54°. The vertical displacement of the source, which was simultaneously available to the subject, was also quite modest (less than 30% of that required with the array in the vertical configuration). The inverse also appears to be true. The presence of a 0.31° difference in the relative azimuth of two sources when combined with a 1.78° difference in elevation can also be resolved. In summary, the current results indicate that concurrent changes in the relative azimuth and elevation can be appreciated even though the change in each dimension is considerably less than that which would be required if it were presented alone. In fact, changes in elevation or azimuth are *least* detectable when presented alone. There is little evidence in these data to suggest that with the sources orientated in an oblique array, the subjects resolved the task by relying exclusively on changes in elevation or azimuth.

Post hoc tests conducted on two of our subjects under monaural listening conditions indicate that performance under all conditions examined in the current study is dependent upon binaural processing. With the elimination of input to one ear, MAA thresholds obtained for sources in the vertical orientation increased by over 200 percent. Under monaural conditions, the rotation of the array to 45° resulted in an increase in the MAA threshold by nearly 1000 percent. It seems clear that, with broad bandwidth stimuli, information regarding the elevation and azimuth of the source is embedded in the signals at each ear. More to the point, the present results indicate that the auditory system is able to appreciate a one-degree angular change in the relative locations of two successive events, as long as some minimal difference in azimuth is present.

ACKNOWLEDGMENTS

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[1]The head movements observed by Thurlow *et al.* (1967) were obtained during sessions in which subjects were attempting to localize a sound source. We have seen the same patterns of head movements both in situations in which subjects were attempting to locate a sound source, and in tasks in which they were asked to locate a visual target. We believe that the movement patterns encountered are not unique to auditory localization settings *per se*, but probably reflect the underlying mechanical characteristics of the system by which the head is moved relative to the body. For most subjects, as they rotate the head to the right or left, there is a strong tendency to rotate the head about the aural axis (the chin drops down). The magnitude of this tipping motion generally increases as the rotation about the central vertical axis is increased. The cocking of the head is most generally encountered as the head approaches the limits of rotation about the central vertical axis. In effect, the head rotates around a wobbly centroid (Perrott and Saberi, 1989). Whether or not such movements are useful to the auditory system as it collects successive samples of the location of an intermittent or sustained acoustic event, such movements must constitute a primary aspect of the natural conditions of listening.

[2]Minimum audible angle thresholds describe the capacity of the subject to make judgments of the location of one event *relative* to that of a second. We have been using procedures over the last decade (e.g., Perrott and Musicant, 1977) in which the absolute location of the events is jittered within a general region, as opposed to employing a referent source from a fixed location. Our concern has been that when subjects are tested over large numbers of trials with a referent source from a fixed location, they may form some absolute referent system. Thus while the subject, on a given trial, may be unable to resolve the relative location of two sequential events, he may determine that the composite sample was more to the right or left than the average. We believe that jittering the location of the referent improves the changes that the subjects will continue to make spatial judgments on the relative locations of the events even after extensive experience on the task.

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