Minimum audible movement angles as a function of sound source trajectory[a)]

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Auditory resolution of moving sound sources was determined in a simulated motion paradigm for sources traveling along horizontal, vertical, or oblique orientations in the subjects's frontal plane. With motion restricted to the horizontal orientation, minimum audible movement angles (MAMA) ranged from about 1.7° at the lowest velocity (1.8°/s) to roughly 10° at the highest velocity (320°/s). With the sound moving along an oblique orientation (rotated 45° relative to the horizontal) MAMAs generally matched those of the horizontal condition. When motion was restricted to the vertical, MAMAs were substantially larger at all velocities (often exceeding 8°). Subsequent tests indicated that MAMAs are a U-shaped function of velocity, with optimum resolution obtained at about 2°/s for the horizontal (and oblique) and 7–11°/s for the vertical orientation. Additional tests conducted at a fixed velocity of 1.8°/s along oblique orientations of 80° and 87° indicated that even a small deviation from the vertical had a significant impact on MAMAs. A displacement of 10° from the vertical orientation (a slope of 80°) was sufficient to reduce thresholds (obtained at a velocity of 1.8°/s) from about 11° to approximately 2° (a fivefold increase in acuity). These results are in good agreement with our previous study of minimum audible angles long oblique planes [Perrott and Saberi, J. Acoust. Soc. Am. **87**, 1728–1731 (1990)]. In summary, the results suggest that: (1) the ability to detect motion is essentially independent of the path traveled by the source, with one noted exception, sources moving within a few degrees of the vertical plane and (2) auditory resolution of sound sources in motion is a U-shaped function of velocity with resolution degrading as velocities increase or decrease beyond an optical velocity range.

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INTRODUCTION

A. Overview

In an earlier paper (Perrott and Saberi, 1990), we reported the results of an experiment in which minimum audible angles (MAAs) were obtained for sources whose position could vary along horizontal, vertical, or oblique orientations in the frontal plane. MAAs of approximately 1° were observed for sources displaced along the horizontal orientation and 3.6° for sources displaced vertically. Results of these two conditions were well in line with previous experiments of this type (on the vertical: Wettschureck, 1973; Morrongiello and Rocca, 1987; and on the horizontal: Perrott and Pacheco, 1989). When sources were displaced along oblique planes of up to 60° above the horizontal, MAAs remained essentially constant (approximately 1°). At a slope of 70°, MAAs increased to 1.24°. When sources were rotated further above the horizontal (i.e., slope of 80°), MAAs increased to about 1.75°. Only when the array was oriented along the vertical median plane (90° slope) did we observe a substantial elevation in MAAs (3.65°).

For all orientations, with the exception of sources dispersed near the vertical plane, spatial acuity was observed to be essentially constant. Figure 1(a) is a plot of these data in polar coordinates. Resolution along the horizontal plane is depicted by the two points along the horizontal axis (0-180). Vertical acuity is represented by the two points along the vertical axis (90-270), and oblique orientations are represented by the intermediate slopes. As is evident from this figure, angular acuity in the frontal plane is elliptical with the distinct exception of the vertical orientation.[1] The implications of such performance are significant. Consider, for example, the threshold obtained for sources distributed on an oblique plane (with a slope of 70°) presented in Fig. 1(b). The MAA obtained for this orientation is about 1.24 deg. A separation of 1.24° at this slope has azimuthal and vertical angular components of 0.42° and 1.16°, respectively. Note that the MAA obtained for the horizontal orientation was about 1° (i.e., more than twice the size of the azimuthal component here) and the MAA observed for the vertical orientation was about 3.6° (i.e., more than three times larger than the vertical component at a slope of 70°). An analysis of the variance reveals that, in effect, the horizontal component of the 70° oblique threshold is 1.3 standard deviations (s.d.) below the threshold obtained when the sources were distributed horizontally (0° orientation), and the vertical component is 2.57 standard deviations below the threshold obtained for the vertical condition (90°). This means that over 90% of the reversals in the adaptive procedure employed on the horizontal condition alone (0°) were above the horizontal threshold of the 70° orientation and over 99% of the reversals on the vertical orientation alone (90°) were above the

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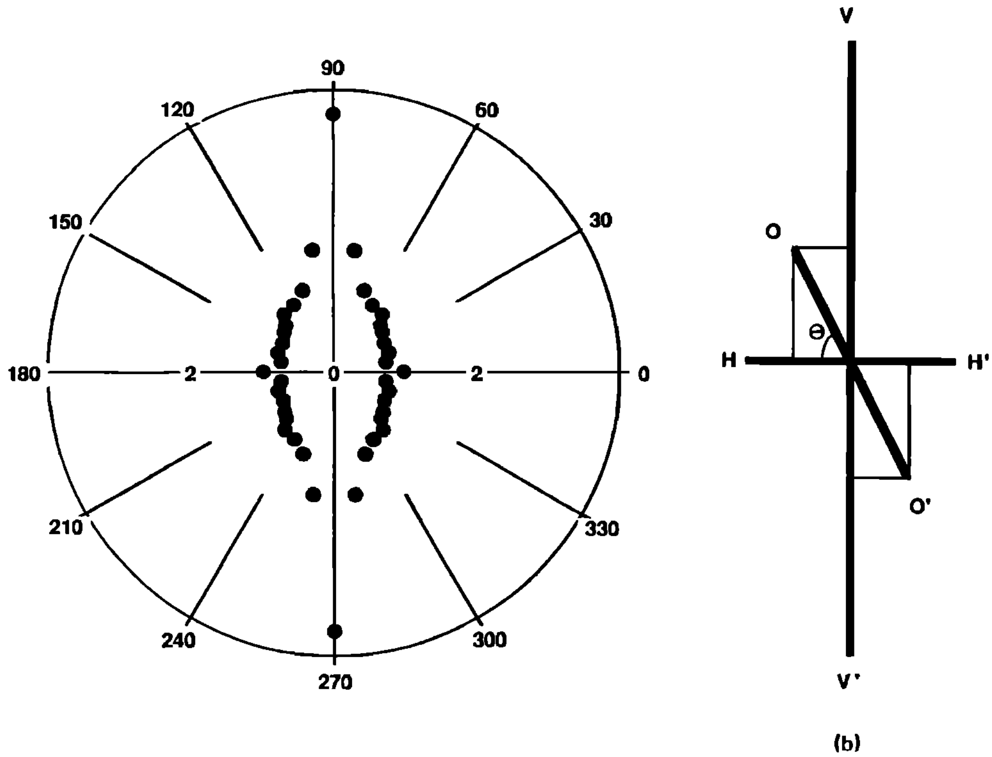

FIG. 1. (a) MAAs obtained for various slopes plotted in polar coordinates. Resolution along the horizontal condition is depicted by the two points along the 0-180 axis. The vertical condition is represented along the 90-270 axis and oblique MAAs are represented by points along intermediate slopes. (b) Line HH' represents the MAA obtained along the sagittal midline (vertical plane). Line OO' represents the MAA obtained for an orientation of 70° above the horizontal plane. The 1.24° threshold at this orientation has azimuthal and vertical angular components (dashed lines) which intersect the horizontal and vertical thresholds (HH' and VV') well inside their terminal points. In other words, the horizontal and vertical cues associated with a 70° slope are each by themselves too small to predict performance along the oblique orientation.

vertical threshold of the 70° orientation.

That subjects could utilize extremely small vertical and horizontal components when these components were *concurrently* present suggests that these cues must somehow be combined within the auditory system. Subsequent experiments at our laboratory have demonstrated that performance along oblique planes substantially deteriorates under monaural conditions. The latter observation suggests that oblique localization occurs within the binaural system or that binaural cues at least play a significant role.[2]

B. Minimum audible movement angles

A great deal of our auditory experience includes encountering sound sources in *motion*. Auditory motion could occur either because the sound source itself is moving or the organism (or its head) is moving while the sound source is stationary or because both the sound source *and* the organism are moving simultaneously. While MAAs are the measure of acuity for *stationary* acoustic targets, minimum audible movement angles (MAMAs) are the measure of auditory resolution of sound sources in *motion* (Perrott and Musicant, 1977). Unlike the MAA, in measuring dynamic spatial acuity (MAMA), one must take into account the added variable of the velocity of the event. MAMAs have been extensively studied using tones for a variety of velocities on the horizontal plane (Harris and Sergeant, 1971; Perrott and Musicant, 1977). MAMAs have also been studied for stimuli with broad bandwidths (Perrott & Marlborough, 1989) and pure tones at various frequencies (Perrott and Tucker, 1988).

Results with broad bandwidth stimuli have typically indicated that performance at lower velocities is similar to that obtained with static sources. MAMAs increase as the velocity of the source increases and as the spectrum is narrowed. For narrow bandwidth signals, spatial acuity of moving sounds is poor for frequencies between 1300–2000 Hz. These results (Perrott and Tucker, 1988) are in good agreement with functions obtained for MAAs (Mills, 1958). The entire literature on MAMAs, however, has been centered on sound sources moving on the horizontal plane (lateral displacement of the source). Given the obvious opportunity to encounter events along various planes in the real world, and that not a single study has explored resolution of moving sound sources along vertical or oblique planes we thought that these other conditions merited consideration.

Various paradigms have been employed in the study of sound sources in motion. They include both real and simulated moving sources. While real motion is in most cases preferable, simulated motion is a practical alternative because of the difficulty of moving a sound source without adding extraneous noise. In addition, one can imagine the experimental constraints and difficulties of physically moving a sound source at broad ranges of velocities and along various orientations. Acoustic simulation of motion has typically involved the dynamic reproduction of interaural differences that result from the actual movement of sound sources. The techniques vary somewhat but have generally involved either increasing or decreasing the interaural differences of time (IDT) or intensity (IDI) for successive dichotic transients presented via earphones in a *lateralization* simulation of motion (Altman and Viskov, 1977) or the concurrent changing of the intensity of two loudspeakers in the *free-field* using inverse time-intensity ramps for each loudspeaker. This latter technique involves the fading off of one speaker while fading on a second speaker (Grantham, 1986). Sustained motion in the free field is simulated by continuing this process for several successive loudspeakers. Steady-state acoustic motion, however, is *not* typical of our experience of most naturally moving sound sources. While sustained vocalization may occur when an organism is in motion, the most common class of naturally occurring "moving sounds" involves abrupt or discontinuous sounds generated by locomotor activity. Such sounds are characterized by broad bandwidth transients (i.e., the breaking of twigs and the rustle of fallen leaves produced as an organism moves across the ground). While we do not argue with the adequacy of paradigms of steady-state simulated or real motion, we have, in the present study opted to employ transient auditory events presented sequentially from a distributed array of sources.

I. METHOD

A. Subjects

Three subjects including the authors participated in this experiment. All three were experienced in psychoacoustical experiments and two of them had participated in the MAA experiment previously described (Perrott and Saberi, 1990). Two had normal hearing based on self-report. Subject DP reported high-frequency hearing loss above 10 kHz.

B. Apparatus

The stimulus consisted of dc pulses (100 μm in duration). Measurements at the output of the speakers [i.e., using a sound level meter (GenRad) and a dual channel storage oscilloscope (Tektronix)] indicated that the acoustic signal was a 1.8-ms broad bandwidth pulse. Signals were presented through thirty 5.7-cm midrange loudspeakers (Quam) mounted on a custom-built boom system that could be rotated through a 90° arc. This boom mounted speaker array was located in a large test chamber ($9.1\times12.2\times2.1$ m). All surfaces of this chamber (including floor and ceiling) had been covered with 10.2-cm acoustic foam wedges (@ Sonex) to minimize sound reflections. Measurements indicated that the chamber had excellent attenuation of reflections down to 500 Hz. Signal intensity measured at the position of the subject's head was 48 dB (A-weighted). All aspects of the experiment were under the control of a microprocessor.

C. Procedure

The subject was seated 716 cm from the speaker array. Head position was fixed during testing by a chin clamp. At the beginning of each trial, one of the ten speakers located in the middle of the array was selected as the starting point from which a single click was emitted. This was followed by clicks from successive speakers in one direction to simulate motion in that direction (either left or right for horizontal and up or down for the vertical condition). The position of the initial speaker on each trial was varied among the center ten speakers to reduce potential spectral cues from unique impulse responses of the speakers. The interpulse interval (IPI) was set at a previously selected value corresponding to a specific velocity. Feedback was presented immediately if the subject correctly identified the direction of travel of the sound on that trial. On the next trial, the starting point was again randomly selected from one of ten centrally located loudspeakers on that array. In effect, the location of the starting point was varied randomly from trial to trial. With the boom in the horizontal orientation, the minimum angular separation between adjacent speakers (center to center) was 0.46° azimuth. The IPIs used were 2, 4, 8, 16, 32, 64, 128, and 256 ms, corresponding to velocities of 230, 115, 57.5, 27.7, 14.4, 7.2, 3.6, and 1.8°/s. Within each session, subjects were tested at one velocity and with the speaker array oriented in one of the following configurations: 0° (horizontal orientation), 45°, or 90° (vertical orientation). With the array on the horizontal plane, the subjects task was to indicate whether the sound moved to the right or left. With the array on the vertical plane, subjects indicated whether the sound moved up or down. The array was always rotated clockwise, therefore for the 45° conditions "up" and to the "left" or "down" and to the "right" were the same. Subjects were allowed to make *either* judgment.

A single-interval, two-alternative forced-choice, three-down one-up adaptive procedure was used to estimate movements yielding 79.4% correct (Levitt, 1971). A single "incorrect" response resulted in an increase of 5.7 cm in the length of travel of the sound for the next trial. Three successive "correct" responses resulted in an equivalent decrease in the path traveled. Fifty reversals were obtained within a session, with the last 30 reversals being used to calculate an estimate of the MAMA.

II. RESULTS

Figure 2 presents the MAMAs obtained for each subject for various velocities under the three orientations of 0° (horizontal), 45°, and 90° (vertical). The lower right panel presents a summary of these data. For velocities of up to 14°/s there appears to be good agreement between MAMAs for array orientations of 0° (horizontal) and 45°.[3] As velocities increase beyond this point, the two functions show greater fluctuation although they generally retain good correspondence. An analysis of variance between orientation (horizontal and oblique) and velocity demonstrates an effect for velocity [$F(7,14) = 28.39$, $p < 0.001$], no significant difference between the oblique and horizontal orientations ($p > 0.05$) and no interaction between velocity and these two orientations ($p > 0.05$).

MAMAs obtained for the vertical condition are significantly higher than the other two orientations. The results of the vertical condition, however, are surprising in that unlike the other conditions a U-shaped function was obtained with optimum performance observed at velocities between 7–11°/s. MAAs obtained through subsequent experiments with the same IPIs (e.g., 256 ms) and the exact same stimuli on the vertical plane were less than a third of the MAMAs for that dimension. Perhaps the most plausible explanation is that for lower velocities the time it takes a sound on the vertical orientation to travel a noticeable distance is too long for an optimum comparison of the start and end points of travel. To test this, we eliminated the middle clicks in the MAMA task (reverting to the MAA task) and measured

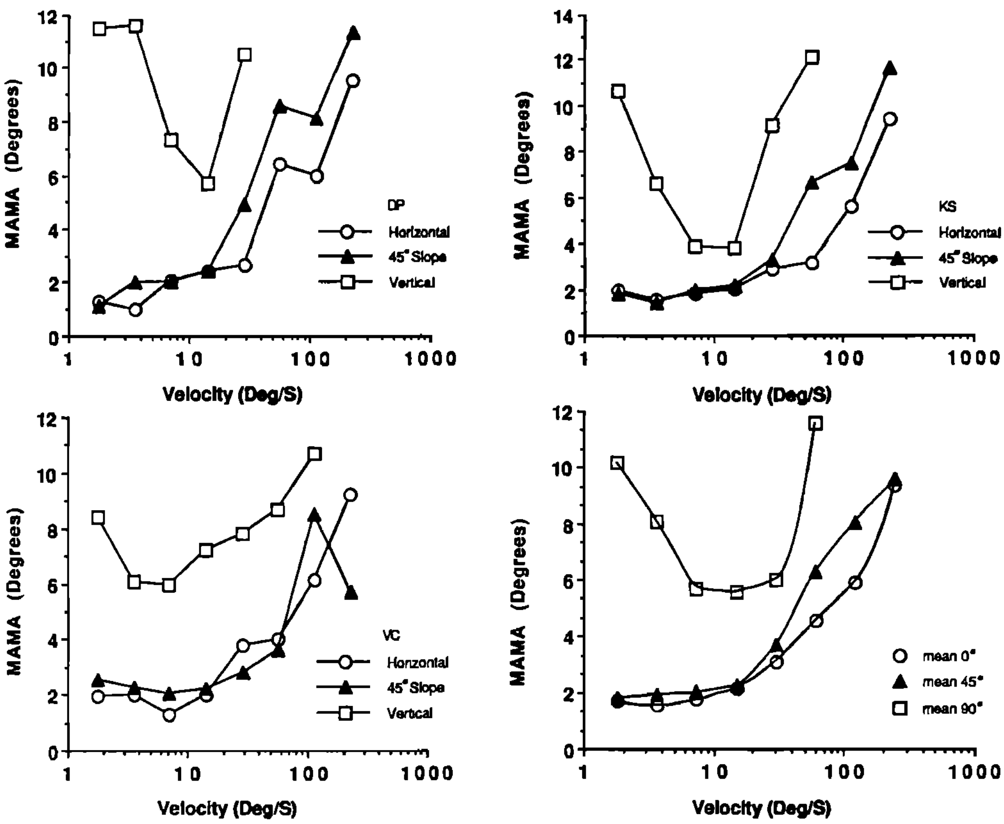

FIG. 2. MAMAs obtained for three subjects as a function of the velocity of the source and the orientation of the array. The lower right panel is the mean for the three subjects.

separation thresholds. What the subjects heard in this modified task was the first click followed by a long IPI (equal to the time it would have taken for the sound to travel from the initial position to the final position if the middle clicks were present) followed by the final click. This travel time could be in excess of 10 s at the lower velocities. The results supported the notion that the lower portion of the velocity function on the vertical plane is due, at least in part, to the very long observation interval required. Thresholds in this now modified MAA task were substantially elevated and resembled those of the MAMAs at the lower velocities. Subsequent experiments were conducted on two of the three subjects to see if the U-shaped function observed for the *vertical* orientation could also be observed in the *horizontal* condition if lower velocities were employed. The results of this experiment are plotted in Fig. 3. When the velocity of a sound source is lowered or increased beyond a certain range, performance seems to deteriorate regardless of sound source trajectory. Note, however, that the optimum velocities for the detection of motion appears to be somewhat higher for sound source movement along the vertical dimension than on the horizontal and oblique.[4]

Further tests conducted at orientations of 80° and 87° demonstrated that even a small deviation from absolute vertical (e.g. 87° condition) results in a substantial improvement in the MAMA. Figure 4 presents the mean MAMAs at 1.8°/s for various array orientations (including orientations of 80° and 87°). These results are presented together with the mean MAAs obtained by Perrott and Saberi (1990). At a velocity of 1.8°/s, MAMAs on the vertical condition are about 10°. A 10° deviation from vertical (80°) provides MAMAs approximately 1/5 of the vertical MAMA and similar to thresholds obtained along the horizontal plane (0° condition). Although MAMAs obtained at 1.8°/s are generally higher than the MAAs obtained for static sources, the results are similar. At orientations other than vertical, thresholds for both static (MAA) and dynamic (MAMA) sources are relatively small and generally constant (approximately 1° for MAAs and 1.5° for MAMAs).

III. DISCUSSION

A. Effects of sound source trajectory

The results of the present study on MAMAs are in good agreement with those of our previous study of MAAs. These results demonstrate that auditory spatial acuity for a sound source in motion is essentially independent of the sound source trajectory with one exception: sources displaced along vertical or nearly vertical orientations. Figure 5 is a polar plot of MAMAs for a single subject at a velocity of 1.8°/s. In this case as in the case of MAAs, the spatial map for the dynamic resolution of sound sources in the frontal plane is constant for most orientations. A precipitous increase in thresholds is evident, however, as one approaches the sagittal midline.

The arguments set forth at the beginning of this paper for MAAs seem to also hold for MAMAs. Consider, for example, thresholds obtained at a velocity of 1.8°/s for subject KS. The MAMA for this subject at a trajectory of 80° relative to the horizontal is about 2.30°. This MAMA, when described in terms of its horizontal and vertical components, yields values of 0.40° and 2.26°, respectively. Note that the horizontal MAMA (1.96°) is more than four times greater than the horizontal angular component of the 80° oblique

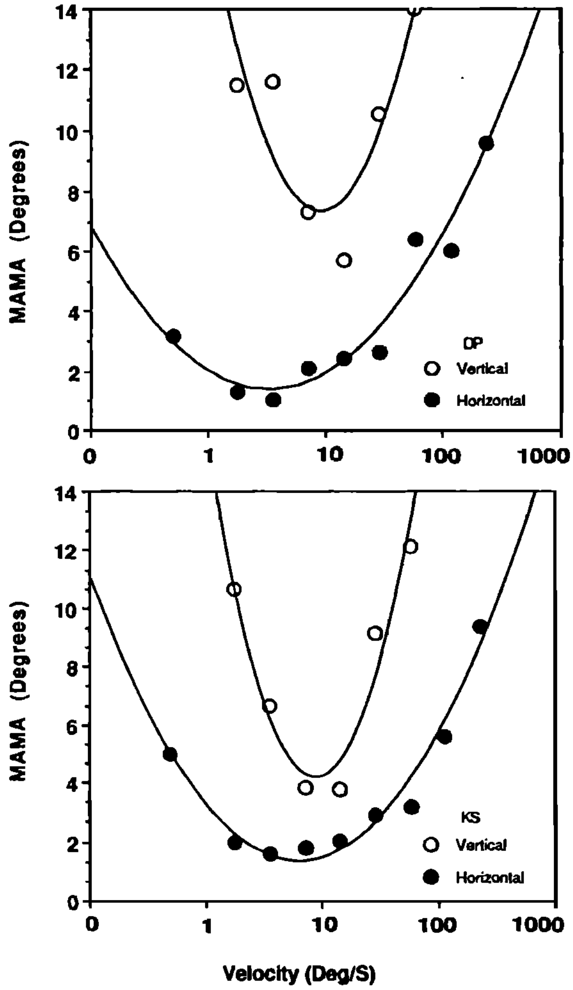

FIG. 3. A reduction of sound source velocity below 1°/s demonstrates how the functions obtained for orientations of 0° (horizontal), and 90° (vertical) are U-shaped functions. The data are from subjects DP and KS.

threshold (0.40°). And the vertical MAMA (10.65°) is also over four times greater than the vertical angular component of the 80° oblique threshold (2.26°). An analysis of the variance demonstrates that the horizontal component of the oblique threshold is about 2.78 standard deviations below the absolute horizontal threshold (at 0° orientation). The vertical component is approximately 7.95 standard deviations below the MAMA obtained with the array in the vertical condition (90° slope). This means that over 99.9% of the threshold crossings on the horizontal condition (0° slope) were above the horizontal component of the oblique threshold and over 99.99% of the threshold crossings obtained for the vertical condition alone were above the vertical component of the 80° oblique condition. Further analysis of the variability shows that approximately 99.9% of threshold crossings at the horizontal are exclusive of (and larger than) 99.9% of the threshold crossings for the horizontal component of the oblique (80°). The same is true for the vertical condition.

The question of whether the cues associated with the horizontal and vertical dimensions are simply summed or whether they interact when both are present (i.e., in the oblique orientation) is one that merits consideration. One

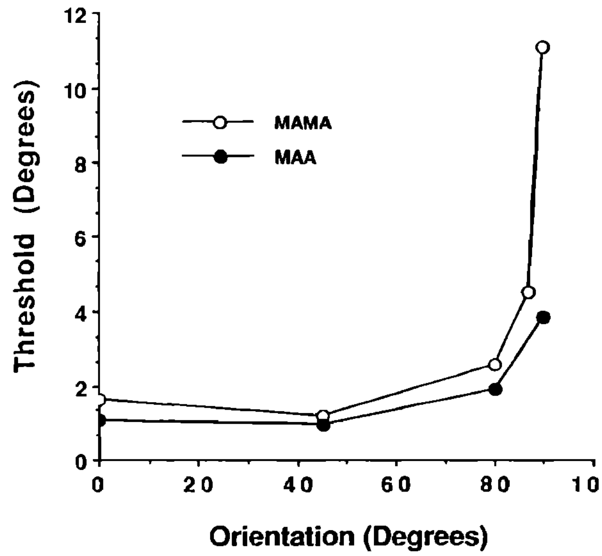

FIG. 4. Mean MAAs (Perrott and Saberi, 1990) obtained from two subjects plotted together with the mean MAMAs obtained for the same two subjects from the current study.

explanation is that the auditory spatial system acts on two largely *independent* processes, a horizontal detector h, which calculates interaural differences in time and intensity (IDT and IDI), and a vertical detector v, which processes changes in the shape of the spectrum at each ear. Assuming an optimum combination of the d' associated with each process (d'_h and d'_v), one can vectorially calculate their sum by

$$d'_0 = (d'^2_h d'^2_v)^{1/2}.$$

This model (Green, 1989) predicts the data fairly well for most slopes, with the exception of the 70°–87° orienta-

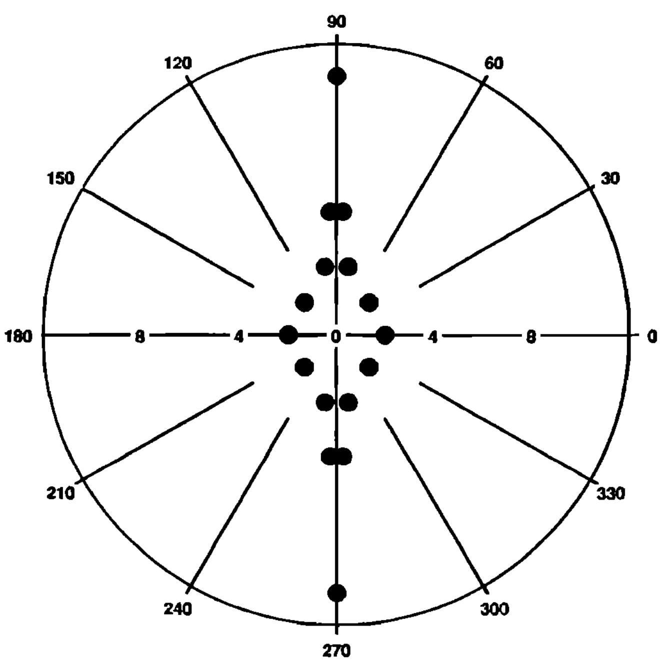

FIG. 5. A polar plot of the mean MAMA for one subject in the present study for a velocity of 1.8°/s as a function of trajectory. Auditory spatial resolution to sound sources in motion seems to be relatively constant with the exception of sources traveling within a few degrees of the vertical plane.

tions. In the latter situations, the model systematically predicts larger thresholds than were actually observed.

An alternative explanation, however, is that IDTs and IDIs might *interact* with binaural spectral differences. For example, interaural differences in sound spectrum due to variations in elevation could result in binaural variations in signal level (probably at specific frequency regions) which might greatly exceed the nominal effect due to the head shadow alone (Butler, 1975). In effect, the interaction of the sound waves with the pinna, torso, etc. (Kuhn, and Guernsey, 1983; Shaw, 1974) can be dependent upon the azimuth as well as the elevation of the source relative to these various surfaces since the head is not a featureless sphere nor is it floating freely in space.

B. Effects of sound source velocity

Figure 3 suggest that there is an optimum sound source velocity for various sound source trajectories. This optimum window of best performance is typically observed to be between 1.8° and 11°/s for all trajectories but the vertical. For the vertical condition we observe a generally narrower window and a more precipitous function. As the velocity of the source decreases below 1.8°/s, it becomes increasingly difficult to judge the direction of movement (again the lower limit for a vertical trajectory is higher). Conversely, as the velocity increases beyond about 11°/s we note a significant decline in spatial acuity.[5] The increase in MAMAs observed at the higher velocities have been noted earlier (Perrott and Musicant, 1977; Perrott and Tucker, 1988) and suggest that relatively long time constants exists in the auditory system. Similar constraints have also been reported for the detection of motion in the visual modality (e.g., Orban *et al.*, 1985). In effect, the ability of the nervous system to appreciate motion seems generally to be "tuned" to a relatively narrow range of velocities.

In summary, the results of the current study suggest that auditory organization of spatial acuity for sound sources moving in the frontal plane is largely independent of the sound source trajectory, with the exception of sound sources traveling along the vertical orientation, and that this function holds with little fluctuation for velocities of at least up to 230°/s. Finally, a constant elevation in thresholds across orientations is observed as the velocity is increased or decreased beyond an optimum velocity.

ACKNOWLEDGMENTS

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[1]The data were collected for the regions between 0° to 90° and 180° to 270°; thus, the polar plot assumes that the two unmeasured polar quadrants (90°–180° and 270°–360°) are the mirror images of the first two.

[2]We should note that the speaker array in the MAA experiment was set at a fixed slope during an entire run; thus, subjects were well aware of it's orientation. In effect, the source was to the right and down or to the left and up relative to the referent; the vertical–horizontal dimensions were correlated. Currently, we are collecting data under conditions where the orientation of a loudspeaker is randomized within the same run in one of the four quadrants in a Cartesian coordinate system.

[3]It should be noted that most natural velocities encountered are in the region where we have observed steady performance (about 14°/s or less). For instance, the sound associated with an animal in motion at a velocity of 25 km/h at a distance of 30 m travels at a rate of about 13°/s.

[4]This, as stated earlier, is probably due to the fact that, when a sound source is traveling along an absolute vertical orientation at a set velocity, it takes it longer to be displaced a noticeable distance than if the same sound was traveling with the same velocity along any other orientation. Similar results have been obtained in the visual modality. That is, very slow movements are difficult to detect (Orban *et al.*, 1985). In that literature, as in our results, probably different factors are responsible for the upper and lower limits of motion detection.

[5]That we have observed an optimal velocity region for resolution of sound sources in motion could have similar implications for the study of static source resolution. While the upper temporal limits between two sources in a MAA task has been previously studied (Perrott and Pacheco, 1989), the lower limits have not been explored. There is no compelling reason to believe that as the interval between the presentation of two sounds in an MAA task is increased, performance would remain intact. In fact, our experiments (as reported in this paper) have demonstrated that MAAs do increase as the time required between the presentation of the two sources is increased. This would mean that there is also an optimum temporal separation for sources in MAA experiments.

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