Minimum Audible Angles for Horizontal, Vertical, and Oblique Orientations: Lateral and Dorsal Planes

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Summary

Minimum audible angles (MAA) were measured using broadband noise bursts for sources whose position could vary along horizontal (0°), vertical (90°), and oblique (61°) orientations relative to the subjects' aural axes. The measurements were made in two planes: 1) the subjects' lateral, and 2) dorsal planes. Results in the lateral plane indicate that auditory resolution is poor along horizontal and oblique orientations relative to MAAs obtained (previously by the authors) for the same orientations in the frontal plane. Vertical acuity, however, was similar to acuity reported for the frontal plane. Substantial intersubject variability was observed for the oblique and horizontal, but not the vertical condition. No statistically significant differences were observed between the various orientations in the lateral plane. MAAs measured in the dorsal plane were much more stable and similar to MAAs obtained in the frontal plane. Interpolation through the three orientations in the dorsal plane suggests that MAAs increase non-linearity (positively accelerating) as slopes increase from the horizontal to the vertical [$F(2,2) = 25.75$, $p < 0.05$].

Kleinste hörbare Winkel für horizontale, vertikale und schräge Orientierungen: laterale und dorsale Ebenen

Zusammenfassung

Unter Verwendung von breitbandigen Rauschimpulsen wurden die kleinsten hörbaren Winkel gemessen für Schallquellen, deren Lage in horizontaler, in vertikaler und schräger Richtung bezüglich der Versuchsperson verändert werden konnte. Die Messungen wurden in zwei Ebenen vorgenommen: 1. in der lateralen und 2. in der dorsalen Ebene der Versuchspersonen. Die Ergebnisse für die laterale Ebene zeigen, daß die gehörmäßige Auflösung in horizontalen und schiefen Richtungen klein ist im Vergleich zu den Winkelschwellen, die für die gleichen Richtungen in der frontalen Ebene gefunden wurden (Perott und Saberi [7]). Die vertikale Wahrnehmungsschärfe war dagegen ähnlich der für die frontale Ebene. Erhebliche Unterschiede für verschiedene Versuchspersonen wurden für schräge und horizontale Richtungen beobachtet, nicht aber für vertikale. In der lateralen Ebene wurden keine signifikanten Differenzen zwischen den verschiedenen Richtungen beobachtet. In der dorsalen Ebene waren die gemessenen Schwellen viel stabiler und ähnlich denjenigen, die für die frontale Ebene gefunden wurden. Eine Interpolation zwischen den drei Richtungen in dorsalen Ebenen legt den Schluß nahe, daß die Schwellen nichtlinear ansteigen (und zwar zunehmend) für Steigungen, die von horizontal nach vertikal zunehmen. [$F(2,2) = 25{,}75$, $p < 0{,}05$].

Les seuils auditifs de déplacement angulaire en orientations horizontale, verticale et oblique: résultats dans les plans latéral et dorsal

Sommaire

On a mesuré les seuils de perception auditive des déplacements angulaires (MAA) en utilisant des impulsions de bruit à large bande et des sources dont la position variait selon les orientations horizontale, verticale et oblique par rapport à l'axe aural des sujets. Ces mesures ont été effectuées 1°) dans le plan latéral et 2°) dans le plan dorsal des sujets. Les résultats dans le plan latéral indiquent que la résolution auditive pour les orientations horizontale et oblique est pauvre comparativement aux MAA obtenus pour les mêmes orientations en plan frontal dans des expériences antérieures de Perrott et Saberi. Cependant l'acuité verticale est comparable à celle dans le plan frontal. La variabilité inter-individuelle était considérable en conditions obliques et horizontale, mais non en verticale. Aucune différence statistiquement significative n'a été observée sur le plan latéral entre les différentes orientations envisagées. Les MAA mesurés en plan dorsal sont beaucoup plus stables que ceux obtenus en plan frontal, mais ils leur ressemblent. Une interpolation entre les trois types d'orientations suggère que les MAA croissent d'une manière non linéaire (avec une accélération positive) lorsque la pente des présentations obliques passe de l'horizontale à la verticale, selon la formule [$F(2,2) = 25{,}75$, $p < 0{,}05$].

Received 18 June 1990, accepted 16 December 1990.

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ACUSTICA
Vol. 75 (1991)

1. Introduction

Minimum audible angles (MAA) have recently been reported (Perrott and Saberi [8]) for sources whose positions could vary along both azimuth and elevation (oblique planes). Fig. 1 a is a plot of MAAs as a function of the slope at which resolution was measured. MAAs were about 1° along the horizontal plane and 3.6° for sources distributed vertically. MAAs measured along oblique slopes, however, remained essentially constant (about 1°) with little loss of acuity as the slopes were increased. The implications of these results are significant. Consider, for example, the case where sources are distributed along a 70° slope. Figure 1 b is a plot of such a condition. MAAs obtained at a slope of about 70 degrees (line OO′) are about 1.24 degrees (data from Perrott and Saberi). Lines HH′ (1 degree) and VV′ (3.6 degrees) represent MAAs measured along the horizontal and vertical orientations. If OO′ is viewed in terms of its horizontal and vertical angular components (dashed lines), then one observes that these components intersect lines HH′ and VV′ well inside their terminal points. Since each component of the oblique array is by itself too small to determine performance, then these components are probably combined at some point within the auditory system to determine oblique performance. Similar results have also been observed with the dynamic resolution of sound sources in motion (Saberi and Perrott [9]).

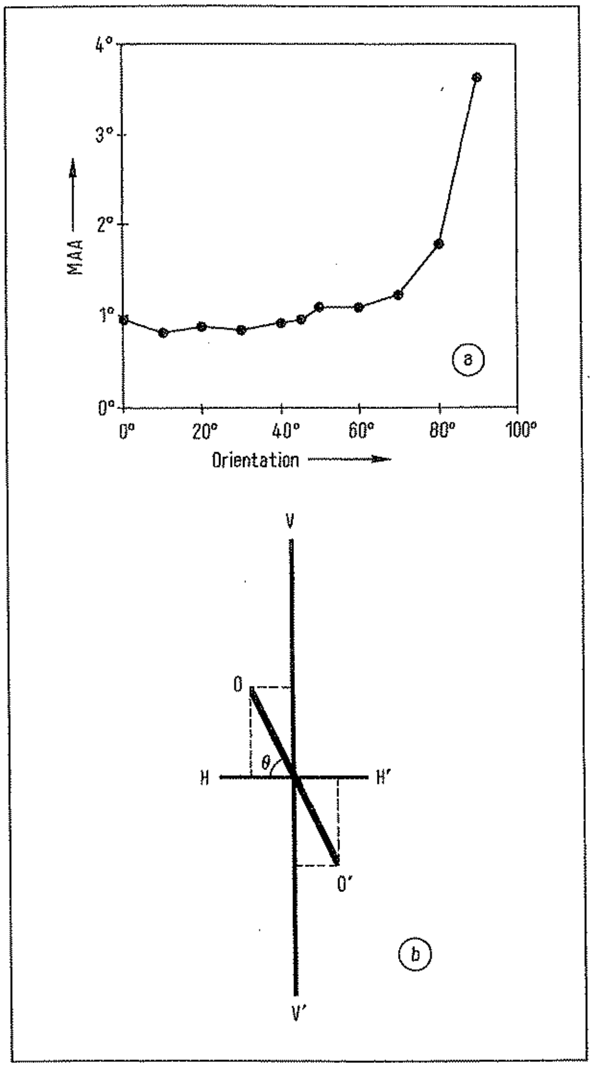

Fig. 1. a) MAAs along oblique planes (Perrott and Saberi, [8]). b) Line OO′ represents the MAA obtained along a slope of 70 degrees. Lines VV′ and HH′ represent MAAs for vertical and horizontal orientations respectively. Note that the horizontal and vertical angular components of the oblique threshold (dashed lines) terminate well inside the MAAs for either the horizontal or vertical alone.

Green [1] has suggested a model to interpret these results. The model assumes that the auditory spatial system operates on two largely independent processes. One is a horizontal detector, h, which calculates interaural differences of time, and the other a vertical detector, v, which detects changes in the power spectrum. If Θ is the angle by which the array is rotated from the horizontal plane, then a change in location (Δm) along the oblique array, results in a horizontal cue $\Delta m \sin \Theta$ and a vertical cue $\Delta m \cos \Theta$. Each of these cues, once weighted by their respective noise, will yield an index of detectability [2] d' (i.e., d'_h and d'_v). Assuming an ideal vector summation of the two processes, the resultant d' for the oblique condition will be determined by:

$$d'_0 = [d'^2_h + d'^2_v]^{0.5}.$$

The model makes fairly good predictions of the data obtained, however, it seems consistently to overestimate the MAAs observed along the larger slopes (70 and 80 degrees).

Among the relatively large body of research which has examined sound localization, little attention has been afforded to acoustic resolution of sources in spatial regions other than the frontal plane. The limited literature that exists (Middlebrooks [3]; Mills [4]; Oldfield and Parker [6]; Stevens and Newman [10]) suggests that resolution is degraded as sources are horizontally displaced away from the sagittal midline. This is probably because the interaural cues associated with horizontal localization on the lateral plane are somewhat ambiguous due to the cone of confusion effect (Wallach [12]; Mills [5]). Vertical resolution on the lateral plane, however, remains relatively intact (Middlebrooks [3]; Oldfield and Parker [6]), since the directional filtering of the spectral cues associated with vertical localization is not substantially degraded.

The present study was conducted to study the resolution of static acoustic sources along horizontal, vertical, and oblique orientations for lateral, and dorsal planes [1]. Given the lack of a substantial literature on planes other than the frontal plane, and given the unexpected results of oblique MAAs, we thought the study of these slopes at different spatial locations merited consideration.

2. Method

2.1. Subjects

Three University students served as subjects. All three had extensive experience in localization experiments and all had normal hearing based on self-report.

2.2. Apparatus

Stimuli consisted of 250 ms wide band white noise bursts presented from 5.7 cm light weight, midrange Quam speakers. The signal sound pressure level was set at 60 dB (A weighted) measured at the position of the subject. A single loudspeaker (referent) was attached to the centre of a locally constructed boom system. Another speaker (comparison) was affixed to one end of the boom which was counter-balanced for weight at the opposite end (see Fig. 2). The boom mounted speaker could be slid along the boom to produce different angular separations (between referent and comparison speakers), however, this angle was kept constant within each run. The boom was attached to a computer-controlled stepper motor which could rotate the comparison speaker through a 360 degree arc in steps of 1.8 degrees (200 locations). Speaker wires were connected to a slip ring to allow continuous motion in any direction. Velocity of rotation was set at approximately 200 degrees/s with an acceleration/deceleration ramp. This boom system was visually blocked from the subjects by a large acoustically transparent cloth screen. All aspects of the experiment were under the control of a separate microprocessor. Experiments were conducted in a large, dimly lit test chamber (9.2 m × 12.2 m × 2.1 m). All surfaces of this chamber (including the floor and ceiling) were covered with 10.2 cm acoustic foam wedges (Sonex @)[2] to minimize sound reflections.

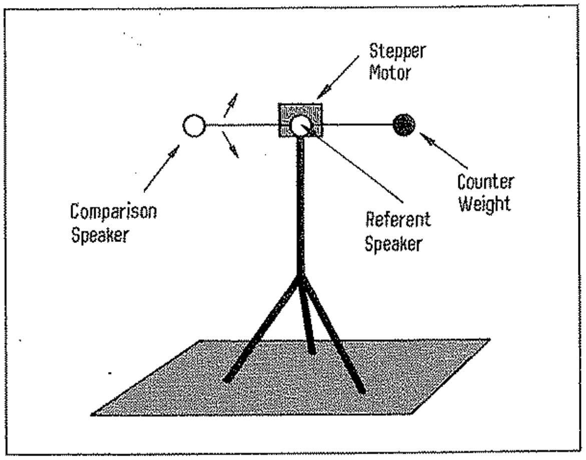

Fig. 2. A schematic representation of the apparatus employed. The stepper motor could displace the light weight comparison speaker in steps of 1.8 degrees, in either direction, and at a rotation velocity of about 200 degrees/s with an acceleration/deceleration ramp. Speaker lines were connected to a slip ring which allowed continuous rotation.

Tests indicated excellent attenuation of reflections down to 500 Hz.

2.3. Procedure

Subjects were seated 310 cm from the speaker system. Each run consisted of 80 trials along only one orientation (horizontal, vertical, or oblique), and in only one plane (lateral or dorsal), and for only one angular separation of the referent and comparison speakers (i.e. the method of constant stimuli). The order of all conditions were completely randomized across angle, orientation, and planes (see Fig. 3). The oblique slope was always set at 61° relative to the horizontal plane (angle θ in Fig. 1 b). The paradigm employed was a two alternative, forced-choice in which the centre speaker (referent) was always activated first. After a 500 ms interstimulus interval the comparison speaker was activated. The subject's task was to indicate at which of the two possible locations the comparison speaker was located (e.g. during a run on the vertical orientation, the comparison speaker would either be placed exactly above the referent or exactly below). Subjects responded via a response panel which communicated these responses to the computer. Feedback was provided after each trial by the computer which would (digitally) voice the correct location to the subjects via a feedback loudspeaker. On each trial the comparison speaker would initially rotate by 90 degrees, with equal likelihood of rotating in either direction (clockwise or counter-clockwise). It would then calculate the terminal point and either rotate through the long arc or the short arc (with equal likelihood) to

[1] The term lateral plane in the present experiment applies to the plane parallel to the median sagittal plane (perpendicular to the interaural axis) but displaced laterally relative to the subject's head. The term dorsal plane applies to the plane parallel to the frontal plane but placed in the rear of the subject's head.

[2] Available from: Sonex Division, Illbruck Inc., 3800 Washington Avenue North, Minneapolis, MN 55412, USA.

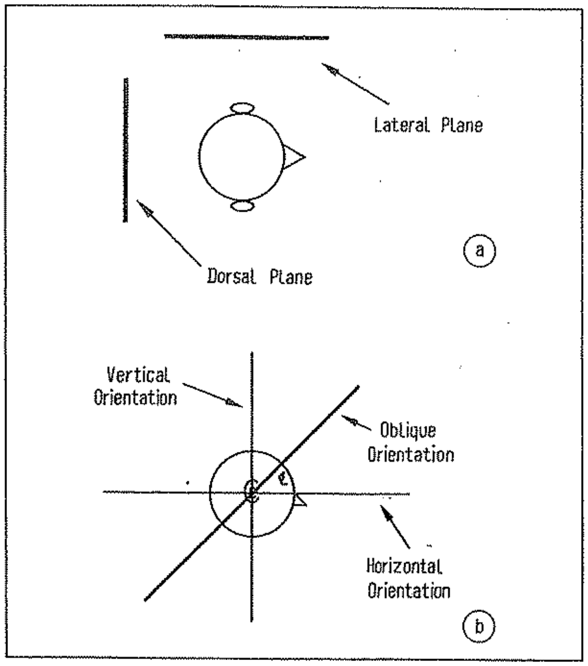

Fig. 3. Upper panel (a) depicts a top view of the two planes studied in the present experiment. Bottom panel (b) shows a side view of the three orientations along which MAAs were obtained in the lateral plane (dorsal plane not shown).

reach this point. The purpose of this two-stop, two-arc rotation was to eliminate any cues which the subjects might have extracted about the location of the comparison speaker from rotation sounds. Tests using this procedure indicated that no cues were available to subjects from the noise associated with the movement of the speaker[3]. During signal presentation, all movements were terminated and no extraneous noise was present. On a given trial, all movements and signal presentations occurred within four seconds. Although no inaccuracies of the stepper motor were observed, after every 20 trials the system would automatically re-calibrate its location and voice the number of remaining trials to the subject. Each session lasted about 7 min.

3. Results

3.1. MAAs in the lateral plane

The triangle symbols in Fig. 4 present the mean MAA thresholds obtained for three subjects at three orientations (horizontal, vertical, and oblique) in the lateral plane. Thresholds are based on a 75 percent correct response level obtained from a least square curve fit to the data. Error bars represent one standard error. Although resolution was generally poorer on the horizontal than on the vertical, the difference was statistically insignificant. These results agree with previous studies where it has been shown that horizontal resolution is degraded with increasing azimuth while vertical resolution is not (Middlebrooks [3]). While there was no statistically significant difference observed between the various orientations in the lateral plane, MAAs did seem to improve (for all subjects) as slopes increased from the horizontal to the vertical. In fact, MAAs in the lateral plane seem to be an inverse function of MAAs in the dorsal plane.

3.2. MAAs in the dorsal plane

The circle symbols of Fig. 4 represent mean MAA thresholds for the same three subjects at the three orientations in the dorsal plane. The shape of this function is similar to the function obtained for MAAs on the frontal plane (Perrott and Saberi [8]), although somewhat larger thresholds were observed along oblique orientations in the dorsal plane than in the frontal plane. Variability is substantially less than that observed on the lateral plane. An analysis of variance test on the data showed a significant effect of orientation [$F(2,2) = 25.75$, $p < 0.05$]. A breakdown of the oblique MAA (1.62°) into its horizontal (0.78) and vertical (1.4) components demonstrates an improve-

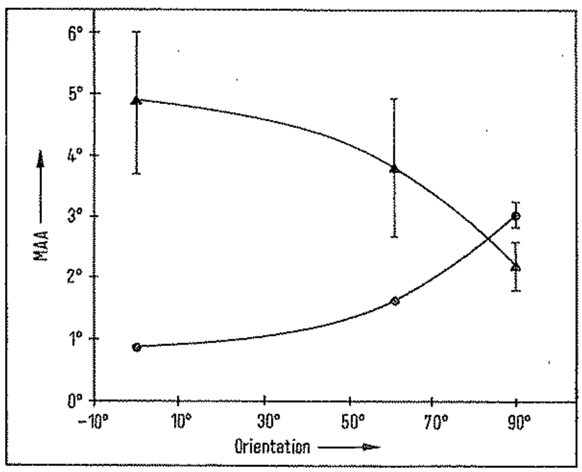

Fig. 4. Triangles represent MAAs obtained in the lateral plane and circles represent MAAs in the dorsal plane. The abscissa represents the orientations along which MAAs were measured. 0° represents the horizontal condition, 61° the oblique, and 90° the vertical. Error bars represent one standard error.

[3] Tests were conducted under conditions in which the speakers were inactive on every trial. Feedback was given on the location of the speaker on every trial after the boom had stopped and the subject had responsed. In effect subjects were to use the sound from motor movements to localize the inactive comparison speaker.

ment over each dimension alone (0.86 and 3.03 degrees for horizontal and vertical MAAs respectively). This is again in agreement with our study of MAAs in the frontal plane. There was no significant difference observed between the vertical conditions in the lateral and dorsal planes. The proximity of the values obtained for the horizontal component of the oblique and the horizontal MAA in the dorsal plane suggests that binaural cues are weighted substantially more than monaural cues. This was noted in our previous paper (Saberi and Perrott [9]) where we observed that performance along oblique orientations degrades under monaural conditions. In the present study, when binaural cues were ambiguous, (lateral plane) performance along the oblique also deteriorated.

4. Discussion

The current study was prompted by the unexpected results of experiments on MAAs along oblique slopes in the frontal plane (Perrott and Saberi [8]). These results indicated that auditory resolution substantially degrades only for sources distributed vertically or nearly vertically. In the present experiments, a similar function was observed for sound source distributions in the dorsal plane. That is MAAs seem to increase non-linearly (positively accelerating) as slopes increased from the horizontal to the vertical. Lateral acuity, however, was poor regardless of orientation. It is noteworthy that relative to the frontal plane, vertical acuity in the lateral plane remained fairly intact while horizontal and oblique acuities were substantially degraded.

We interpret these results in the context of the findings of other researchers, who have reported improvements in auditory localization performance as a result of head movements (Wallach [12]). Thurlow et al. [11] for example, have reported the occurrence of three types of head movements in response to acoustic stimuli; tipping about the aural axis, rotation around the vertical axis, and pivoting about the frontal axis. The pertinence of these movements to the results of the present study becomes evident when one considers the case of sources distributed vertically in the frontal or dorsal planes. Under such conditions, a slight pivot of the head off the vertical axis can result in substantial improvements in spatial acuity since resolution improves non-linearly as the head moves off the vertical axis.

The case of acuity in the lateral plane, however, is different, since auditory resolution seems to be poor regardless of orientation. Nonetheless, head movements here are still probably beneficial to localization since, in addition to displacing the sound source toward the frontal plane, they also result in rotation about more than a single axis. In incidental observations at our laboratory, for example, we have noted a substantial occurrence of concurrent tipping-rotation movements of the head in response to sources which are located in the lateral plane (Perrott et al. [7]). While we acknowledge that associating different types of head movements with specific sound source distributions may be premature at this stage, we would like to postulate that the shape of the auditory spatial function we have obtained could be closely related to improvements observed in localization performance when head movements are allowed.

Acknowledgements

This research was supported by grants awarded to the last author from the National Science Foundation (BNS-8512317) and the National Institutes of Health (3S06 RR0801-1452).

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