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The contribution of two ears to the perception of vertical angle in sagittal planes

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Because the input signals to the left and right ears are not identical, it is important to clarify the role of these signals in the perception of the vertical angle of a sound source at any position in the upper hemisphere. To obtain basic findings on upper hemisphere localization, this paper investigates the contribution of each pinna to the perception of vertical angle. Tests measured localization of the vertical angle in five planes parallel to the median plane. In the localization tests, the pinna cavities of one or both ears were occluded. Results showed that pinna cavities of both the near and far ears play a role in determining the perceived vertical angle of a sound source in any plane, including the median plane. As a sound source shifts laterally away from the median plane, the contribution of the near ear increases and, conversely, that of the far ear decreases. For saggital planes at azimuths greater than 60° from midline, the far ear no longer contributes measurably to the determination of vertical angle. © *2001 Acoustical Society of America.* [DOI: 10.1121/1.1352084]

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I. INTRODUCTION

Most previous studies of sound localization ability have concentrated on localization performance in the horizontal and median planes. It is generally known that binaural disparity cues [i.e., interaural time (phase) differences and interaural level differences] are cues for horizontal-plane localization, while spectral cues (i.e., spectral distortions produced by the pinnae) are cues for median-plane localization. Most previous studies on median-plane localization have treated spectral cues as a monaural auditory phenomenon, since the input signals of two ears from a sound source in the median plane are generally very similar. They have shown that spectral distortions caused by pinnae in the high-frequency range above about 5 kHz acts as cues for median-plane localization (e.g., Roffler and Butler, 1968; Blauert, 1969/1970; Gardner and Gardner, 1973; Hebrank and Wright, 1974a; Butler and Belendiuk, 1977; Watkins, 1978). Only a few studies have speculated that binaural spectral differences contribute to sound localization in the median plane (Butler, 1969; Searle *et al.*, 1975; Duda, 1997). These speculations have been questioned by several experimental findings (Gardner, 1973; Hebrank and Wright, 1974b; Hebrank, 1976; Morimoto and Nomachi, 1982).

If everyday life, however, a sound does not come from only the horizontal and median planes, but may come from any direction around a listener. There is a need to identify localization cues in such a case. Morimoto and Aokata (1984) demonstrated that an interaural-polar-axis coordinate system, as shown in Fig. 1, is more suitable for explaining sound localization in any direction in the upper hemisphere than a geodesic coordinate system defined by the azimuth angle ψ and the elevation angle θ. In an interaural-polar-axis coordinate system, the angle α is the angle between the aural axis and a straight line connecting the sound source with the center of a subject's head, and the angle β is the angle between the horizontal plane and the perpendicular from the sound source to the aural axis, that is, the vertical angle in a plane parallel to the median plane, called the sagittal plane. According to the results of localization tests, Morimoto and Aokata determined that angle α and angle β are independently determined by binaural disparity cues and spectral cues, respectively.

Middlebrooks (1992) constructed a quantitative model of two-dimensional localization in which the azimuth angle and the elevation angle of a subject's response were successfully predicted based on interaural level differences and spectral cues, respectively. In his experiments, the locations of stimuli and responses were specified in a double-pole coordinate system. In this coordinate system, the elevation angle is formed by the sound source (or response location), the center of the subject's head, and the horizontal plane. The azimuth angle is formed by the sound source, the center of the head, and the median plane. This coordinate system is a little different from Morimoto and Aokata's, but the two coordinate systems are similar, in that in both systems, the vertical location is determined in a sagittal plane parallel to the median plane. Accordingly, Middlebrooks' model supports the experimental results of Morimoto and Aokata.

In all geodesic, interaural-polar-axis, and double-pole coordinate systems, there is no doubt that a vertical location of a sound image is determined by spectral cues, though the definition of vertical angle depends on each coordinate system. Spectral cues have been treated as monaural cues in most studies on median-plane localization, as mentioned above. Since input signals to the right and left ears from a sound source in the median plane are generally very similar, it may be appropriate to consider spectral cues to be a monaural phenomenon in median-plane localization. A problem is that the input signals to the left and right ears from a sound

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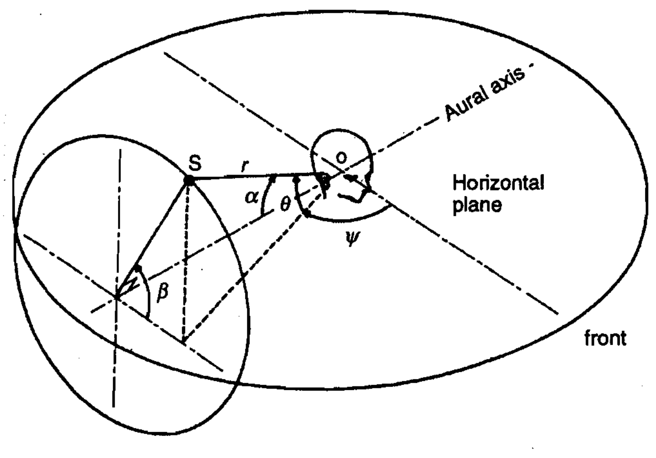

FIG. 1. Definition of an interaural-polar-axis coordinate system. S: sound source; O: center of the head; r: distance between a sound source and the center of head; ψ: azimuth angle; θ: elevation angle; α: the angle between the aural axis and a straight line connecting the sound source with the center of a subject's head; β: the angle between the horizontal plane and the perpendicular from the sound source to the aural axis, that is, the vertical angle in a plane parallel to the median plane, called the sagittal plane.

source outside the median plane are not spectrally identified.

In this case, how do the two ears play a role in the perception of the vertical angle outside the median plane? Musicant and Butler (1984) demonstrated that the ear on the side of the sound source (near ear) contributed powerfully to front–back discrimination, as did the ear on the side opposite the sound source (far ear). Humanski and Butler (1988) showed that the contribution of the near ear was greater than that of the far ear in determining the vertical location of a sound source in the sagittal plane. In both experiments, however, sound sources were arranged only on or near the horizontal plane.

In the present paper, localization tests of sound sources arranged throughout the upper hemisphere were carried out, adopting an interaural-polar-axis coordinate system as shown in Fig. 1. The purpose was to clarify the relationship between the degree of a shift of a sound source from the median plane and the degree of contribution of each ear to the perception of the vertical angle β. In these localization tests, pinna cavities of one or both ears were occluded in the same manner as in the experiments by Gardner (1973) and Humanski and Butler (1988).

II. METHOD

A. Subjects

Subjects were three male students, 22 years of age ±1 year, with normal hearing sensitivity. All were experienced in this type of localization test.

B. Apparatus and stimulus

The localization tests were conducted in an anechoic chamber. The outer walls of the chamber were constructed of 30 cm thick reinforced concrete. Glass wool 25 cm thick was installed on the walls as sound absorbing material. The dimensions of the working area of the chamber were 3.90 m wide, 4.90 m deep, and 3.90 m high. The background noise level was below 20 dB(A).

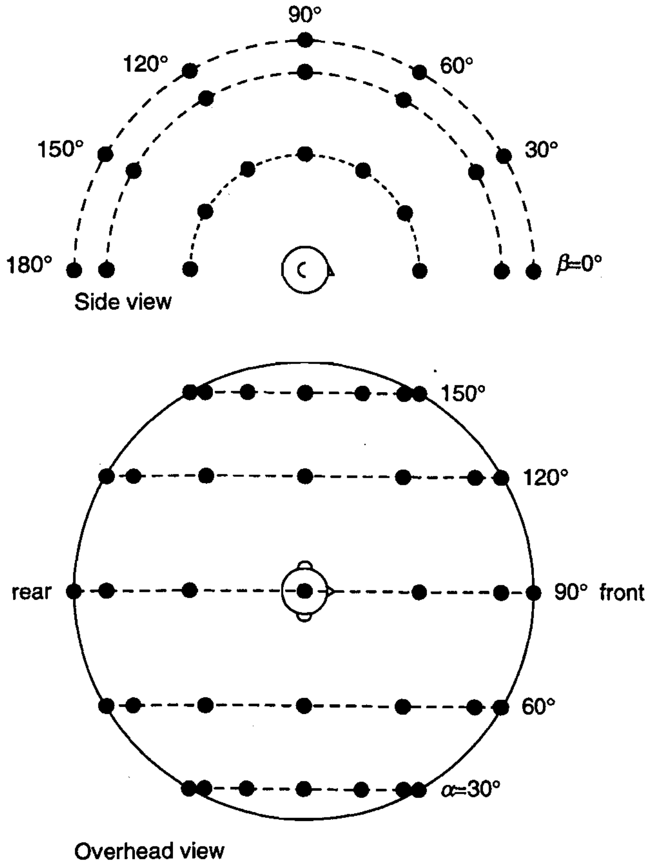

FIG. 2. Arrangement of loudspeakers used for the localization test. In the side view, loudspeakers in sagittal planes defined by angles $\alpha=120°$ and 150° are hidden by those in sagittal planes defined by angles $\alpha=60°$ and 30°, respectively.

Thirty-five small dome-type loudspeakers (Technics EAS-6KH, diameter: 53 mm) were used for the localization tests, as shown in Fig. 2. Their angle α settings were 30°, 60°, 90°, 120°, and 150°, and their angle β settings were 0°, 30°, 60°, 90°, 120°, 150°, and 180°. The speaker radius was 1.6 m relative to the center of the subject's head. The frequency characteristics of the 35 loudspeakers were flattened to within ±3 dB in the frequency range of the stimulus by a frequency equalizer (Technics SH-9090).

The stimulus was a wide band white noise from 1 kHz to 16 kHz. The wide band white noise was generated from a Hewlett-Packard noise generator (model 3722 A) and was delivered to a custom-built timer gate with a abrupt rise–fall time. To establish the filtered noise condition, the burst was routed through an NF active filter (model FV625A), which resulted in a 48 dB/oct rejection slope. After appropriate filtering (bandpass from 1 kHz to 16 kHz), the stimuli were amplified (Onkyo Integra 713) and delivered one of loudspeakers via a custom-built loudspeaker selector. The stimulus was delivered at 50 dB(A) (SPL for 1 s, followed by an interval of 4 s.

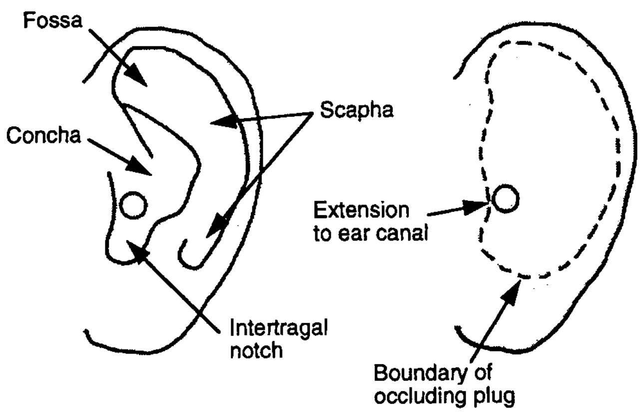

FIG. 3. The occluded part of a pinna.

C. Pinna conditions

The localization tests were done under four pinna conditions: (a) both ears open, i.e., the pinna cavities of both ears were not occluded; (b) right ear open, i.e., the pinna cavities of the right ear were entirely open while those of the left ear were occluded except for a passageway to the ear canal; (c) left ear open, i.e., the pinna cavities of the left ear were entirely open while those of the right ear were occluded except for a passageway to the ear canal; and (d) both ears occluded, as described above. The occluded part of cavities is shown in Fig. 3. In this experiment, the pinna cavities were occluded using a material normally used for dental impressions (Algix), and the passageway to the ear canal was made of a drinking straw. The surface of the occlusion was flattened to be level with the end of the straw and the helix. The length of the straw was almost equal to the distance from the surface to the entrance of the auditory canal.

Head-related transfer functions were measured at the entrance of the passageway of the occluded ear and at the entrance of the auditory canal of the open ear (see the Appendix). Figure 4 shows the head-related transfer functions of one of the three subjects from seven sound sources in the median plane (angle $\alpha=90°$) to the occluded ear, compared with those to the open ear, as an example. Although the occlusion substantially distorted the spectral shape, it still provided consistent spectral information related to the source angle β. But Gardner and Gardner (1973) indicated that localization performance in the vertical plane was dramatically disrupted when cavities of both ears were occluded. Moreover, Hofman *et al.* (1998) demonstrated that more than several weeks were necessary to adapt subjects to new spectral cues after the occlusion and that when occlusion was removed immediately after adaptation, the subjects' localization accuracy with unoccluded ears was still as high as before the occlusion. In the present localization tests, the occlusion period was too short to allow subjects to adapt to spectral cues, as described in Sec. II D.

Another possible effect of the occlusion was to cause possible lateral displacement of a sound image, because occlusion can affect binaural disparity cues, i.e., interaural time (phase) differences and interaural level differences. However, Gardner (1973) stated that if a passageway was provided through the occluding plug, lateral displacements were avoided and the apparent location of the signal remained within, or very close to, the median plane. Accordingly, the occlusion of pinna cavities could be regarded as an adequate manipulation to achieve the purpose of the present paper.

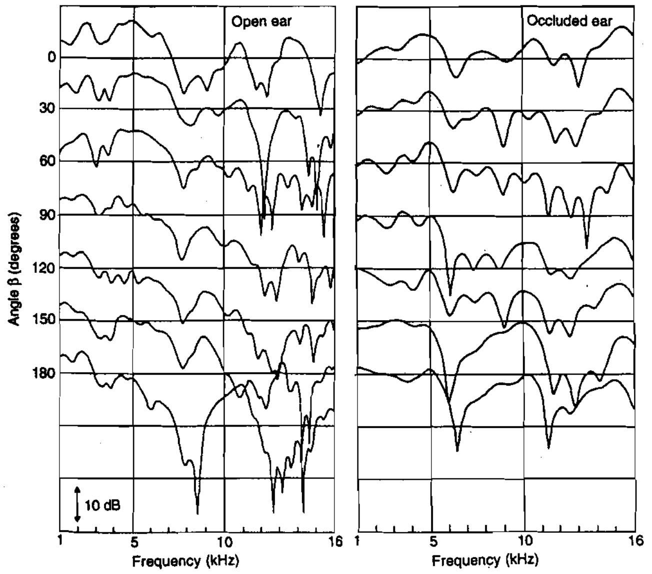

FIG. 4. Measured amplitudes of head-related transfer functions of an open ear (left) and an occluded ear (right). Left ear of one of three subjects. Source angle $\alpha=90°$.

D. Procedure

Each subject was tested individually while seated, with his head fixed in a stationary position, in a partially darkened anechoic chamber. Seventy-seven recording sheets, each with a circle and an arrow on it, were supplied to the subject. An arrow on the top of the circle indicated the 0° of angle β. The subject's task was to mark down the perceived angle β for each one-second stimulus presentation. The 4 s interstimulus interval allowed the subject to pick up the next record sheet. The only light in the chamber was placed such that it provided just enough illumination for the subject to see and utilize the record sheets.

Localization tests for each subject were performed in two days. On the first day, tests for both ears open condition were carried out to confirm the localization ability of the subjects. On the second day, tests for the other pinna conditions were carried out, separated by breaks of about 30 min each in the order right ear open, both ears occluded, and left ear open. For each pinna condition, a subject was tested with each angle α in random order, separated by a break of at least 5 min while he was seated. For each angle α, 11 sets of stimuli were presented successively to the subject. In a set of stimuli, the stimulus was presented once from a loudspeaker at each of seven angles β in random order. The presentation order of the seven angles β was different between sets. Thus each subject made a total of 1540 judgments for the entire task (4 pinna conditions, 5 angle α settings, 7 angle β settings, and 11 presentations for each angle β).

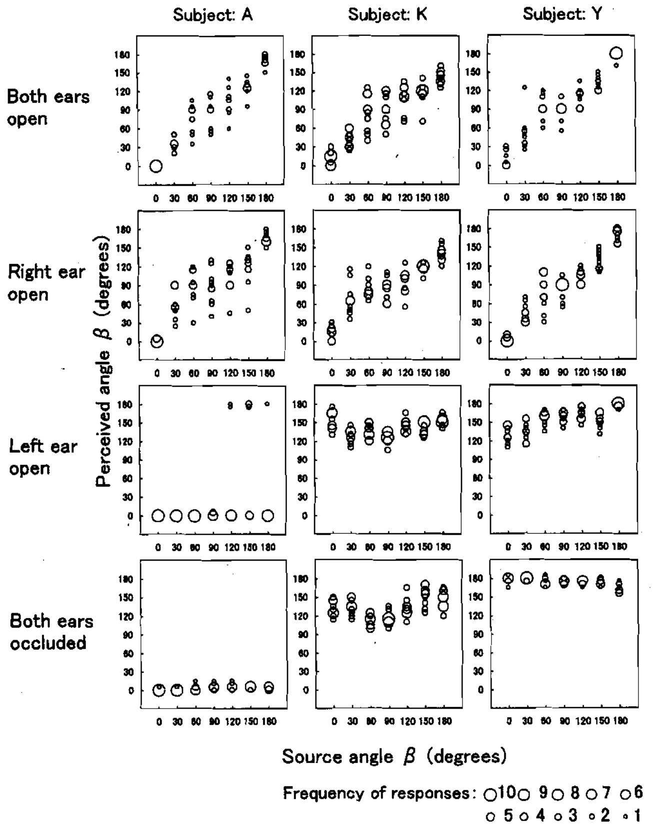

FIG. 5. Subjects localization responses β as a function of source angle β. Each column displays the results for a different subject. Each row displays the results for a different pinna condition (labeled to the left). The diameter of the data points indicates the number of responses, as shown by the key at the bottom. Source angle $\alpha=30°$.

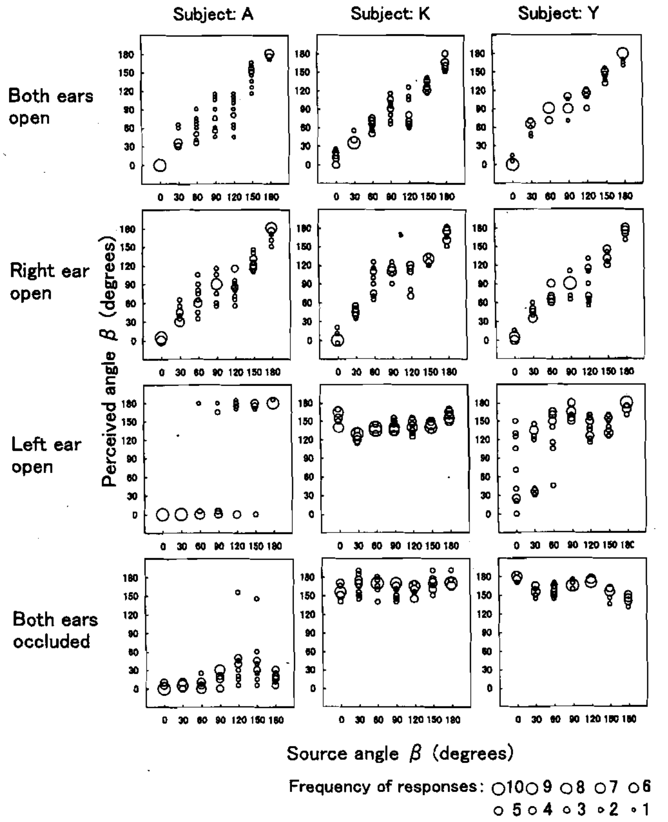

FIG. 6. As Fig. 5 for the angle $\alpha=60°$.

III. RESULTS

Sometimes subjects reported that sound images for sound sources in the median plane (angle $\alpha=90°$) shifted a little to the open ear side. It appears that the pinna occlusion slightly altered binaural disparity cues [i.e., interaural time (phase) differences and/or interaural level differences] as described in Sec. II C. However, Morimoto and Aokata (1984) and Middlebrooks (1992) made clear that angle α and angle β are independently determined. Moreover, subjects who perceived a lateral displacement of a sound image stated that they could judge angle β without hindrance because of the slight displacement. Therefore, the lateral displacement was not regarded as an obstacle to achieving the purpose of the present paper.

Responses to the first test sets for each angle α under each pinna condition were regarded as practice and were excluded from the results. The angle marked by the subject was read with a protractor to an accuracy of one degree.

The effects of pinna occlusion on the perception of angle β in sagittal planes were investigated with distribution charts of subjects' responses. Results are displayed in Figs. 5–9 for angles $\alpha=30°$, 60°, 90°, 120°, and 150°, respectively. Within each figure the three columns show the individual data for the three subjects, and the four rows display the four pinna conditions. The diameter of each circle plotted is proportional to the number of responses within 5°. The ordinate of

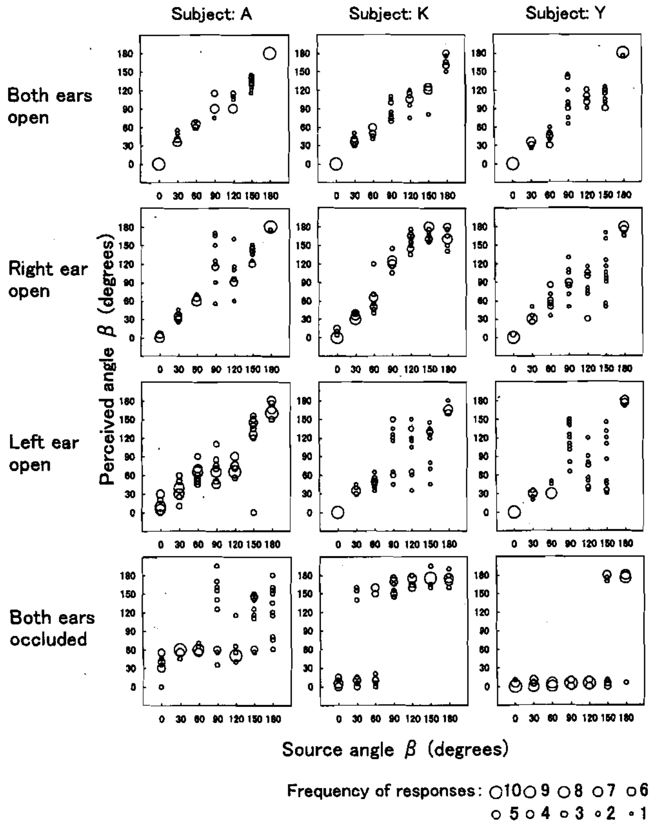

FIG. 7. As Fig. 5 for the angle $\alpha=90°$.

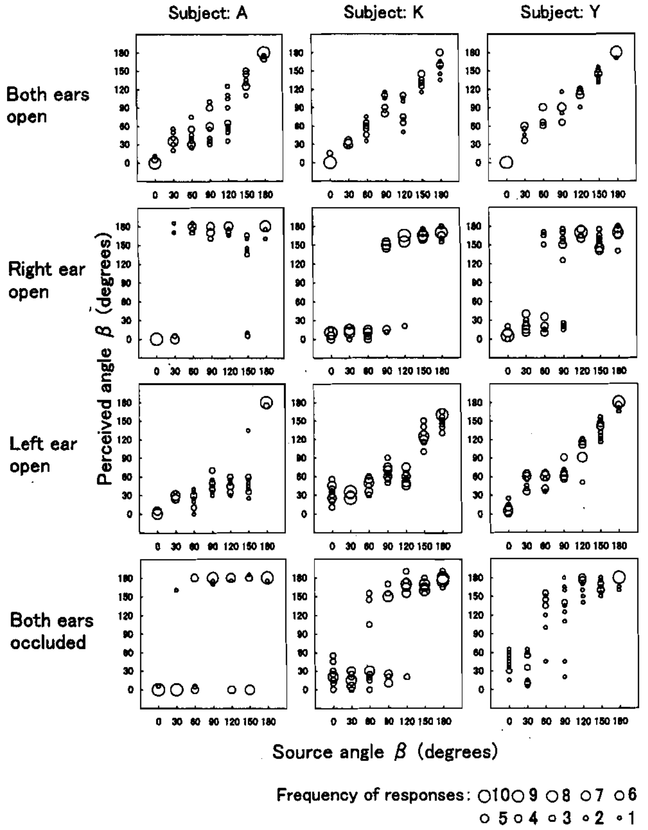

FIG. 8. As Fig. 5 for the angle $\alpha=120°$.

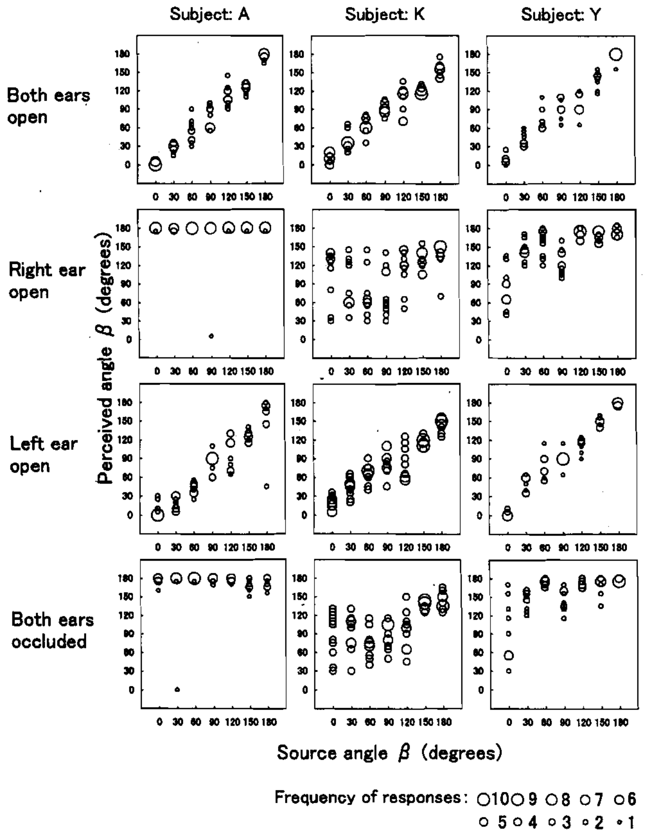

FIG. 9. As Fig. 5 for the angle $\alpha=150°$.

each panel is the perceived angle β, and the abscissa is the source angle β.

Distinct individual differences in localization performance appeared in only two cases: the responses of subject A for angle $\alpha=150°$ under the right-ear-open condition (Fig. 9, second row) and those of subject K for angle $\alpha=150°$ under the both-ears-occluded condition (Fig. 9, bottom row). Although the responses of subject A for angle $\alpha=30°$ under the left-ear-open condition (Fig. 5, third row) and for angle $\alpha=30°$ and 60° under the both-ears-occluded condition (Figs. 5 and 6, bottom row) seem to be different from those of subjects K and Y, a tendency of responses to concentrate in one direction was common to all three subjects. Furthermore, although the responses of the three subjects for angle $\alpha=60°$ under the left-ear-open condition (Fig. 6, third row) seem to differ from each other, a tendency for few responses to appear around angle $\alpha=90°$ and most to be near 0° (front) and 180° (rear) was common to all three subjects. In summary, some individual differences were observed, yet one could see certain general trends.

Figure 7 shows the perceived angles β for sound sources at angle $\alpha=90°$, i.e., in the median plane. When both ears were open (top row), the perceived angles β practically coincided with the source angles β. The variances of the responses for the source angles β around 90° were larger than those for angle β near 0° (front) or 180° (rear). This tendency coincides with localization blur in the median plane (Damaske and Wagener, 1969; Kurosawa *et al.*, 1982). This means that the response method with recording sheets used in the present tests was adequate. When both ears were occluded (bottom row), the perceived angles β were practically independent of the source angles β: most responses shifted to 0° (front) or 180° (rear). Some front–back confusion occurred for every position of source angle β. As a result, the pinna occlusion effectively removed localization cues for the perception of angle β. When either of the ears was open (second and third rows), regardless of the side of the open ear, the source angles β were correctly perceived on the whole, although the variances of the responses for the source angles β from 90° to 150° were larger than those when both ears were open, and some front–back confusion occurred at $\beta=120°$ and 150°.

Figures 5 and 6 show the perceived angles β for sound sources at angles $\alpha=30°$ and 60° on the right of the median plane. When both ears were open (top rows), the perceived angles β practically coincided with the source angles β and front–back confusions hardly occurred, although the variances of the responses were somewhat larger than those in the case of angle $\alpha=90°$ (Fig. 7). When the right ear on the source side was open (second rows), the angles β could be perceived with much the same accuracy as when both ears were open. When the left ear was open, that is, the right ear on the source side was occluded (third rows), few responses appeared around 90° (above) and most of them shifted to 0° (front) or 180° (rear). A considerable number of front–back confusions occurred for every position of source angle β. When both ears were occluded (bottom rows), the angles β were perceived as inaccurately as when the right ear on the source side was occluded.

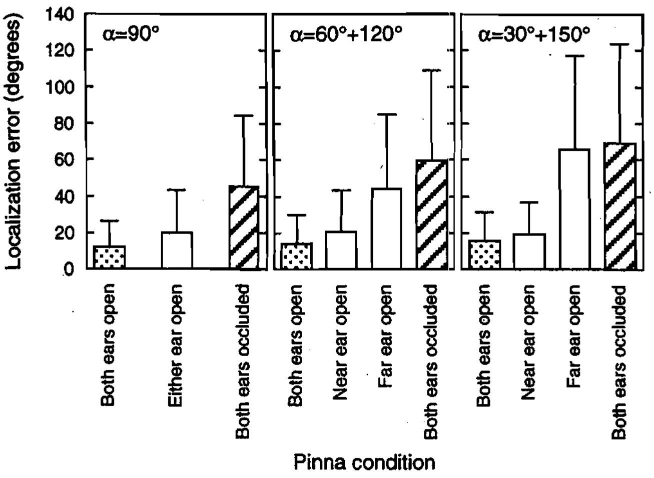

FIG. 10. Effects of pinna condition on localization error. Bars indicate standard deviations.

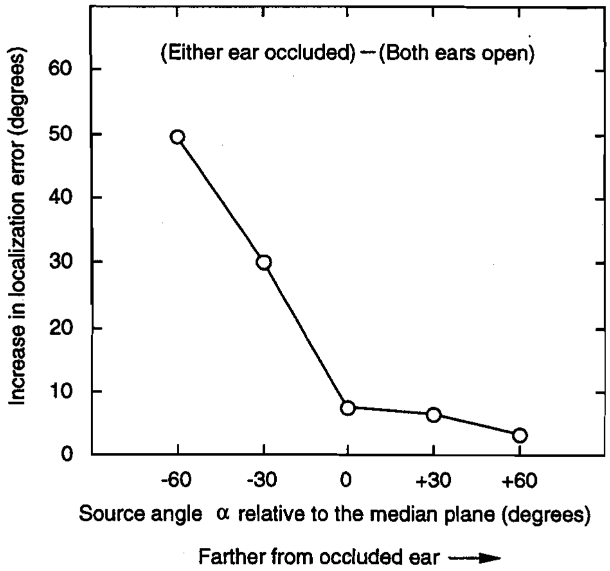

FIG. 11. Effects of either ear occlusion on localization error. Increase in error with either ear occluded relative to the both-ears-open condition.

Figures 8 and 9 show perceived angles β for sound sources at the angles $\alpha=120°$ and 150° on the left side of the median plane. The results in these cases show a similar tendency to those in the cases of $\alpha=30°$ and 60°. Here, of course, the left ear open conditions (third rows) are the cases in which the open ear is one the same side as the source, and are comparable to the right-ear-open conditions considered in the previous paragraph (second rows in Figs. 5 and 6). Similarly, the right ear open conditions (second rows) are comparable to the left-ear-open conditions (third rows in Figs. 5 and 6) for angle $\alpha=30°$ and 60°.

The effects of pinna occlusion on the perception of angle β in sagittal planes may be summarized as follows. When only the ear on the source side was occluded or both ears were occluded, few sound images appeared around $\beta=90°$ (above), and front–back confusions occurred. When only the ear on the side opposite the sound source was occluded, the angle β could be correctly perceived on the whole, while the variances of responses were larger than when both ears were open. These tendencies are very similar to those of sound localization for low-pass noises of less than 4.8 kHz in the median and the traverse planes described in previous papers (Morimoto, 1981; Morimoto and Aokata, 1984).

Figure 10 shows the effects of pinna condition on the localization error in each sagittal plane. The error is defined as the mean absolute deviation of perceived angle from source angle (Morimoto and Ando, 1980). Here, the error was obtained from the responses of the three subjects together, because individual differences among them were not remarkable, as shown in Figs. 5–9. In this figure, the results for $\alpha=60°$ and 120° are combined, and the results for $\alpha=30°$ and 150° are combined, because the results for those two sets of angles can be considered to be symmetrical about the median plane, according to the results shown in Figs. 5 and 9 and Figs. 6 and 8. The near ear and the far ear refer to the ear on the source side and the opposite ear to the source side, respectively.

In the median plane (angle $\alpha=90°$), the error increased in the order both ears open, either ear open, and both ears occluded. For $\alpha=60°$ and 120°, the error increased in the order both ears open, near ear open, far ear open, and both ears occluded. For the more lateral sagittal planes defined by angles $\alpha=30°$ and 150°, the error increased in the order both ears open, near ear open, far ear open, and both ears occluded.

Statistical tests were performed to determine whether or not a difference between mean localization errors for two pinna conditions in each sagittal plane was statistically significant. The statistical method used for the test was the z-test.[1] All three pairwise tests were done for $\alpha=90°$ and all six pairwise tests were done for $\alpha=60°$ and 120° and for $\alpha=30°$ and 150°. The sample size of each group was 420, but it was 210 for only both ears open and both ears occluded in the median plane (angle $\alpha=90°$).

For $\alpha=90°$ (median plane) and for $\alpha=60°$ and 120°, p-values obtained less than 1.0×10^{-6} for all pairs; that is, there were statistically significant differences between all of the conditions. This means that both ears contributed to the perception of angle β, even in the median plane, and suggests that the near ear contributed to the perception of angle β more than the far ear did. For $\alpha=30°$ and 150°, p-values were less than 1.0×10^{-6} for all pairs except two: for the test of far ear open versus both ears occluded the p-value was 0.2717, and for the test of near ear open versus both ears open the p-value was 0.0054. These values suggest that the far ear did not contribute measurably to the perception of angle β in these sagittal planes, although the latter value is similar than a value which is conventionally considered to be a significant level.

Figure 11 shows the effect of occluding either ear on localization error. The ordinate indicates the increase in the error when either of two open ears is occluded relative to the case with both ears open. The abscissa indicates the source angle α as a relative angle to the median plane. Zero means that a sound source is in the median plane. Plus or minus means that a sound source is on the open ear side or the occluded ear side relative to the median plane, respectively.

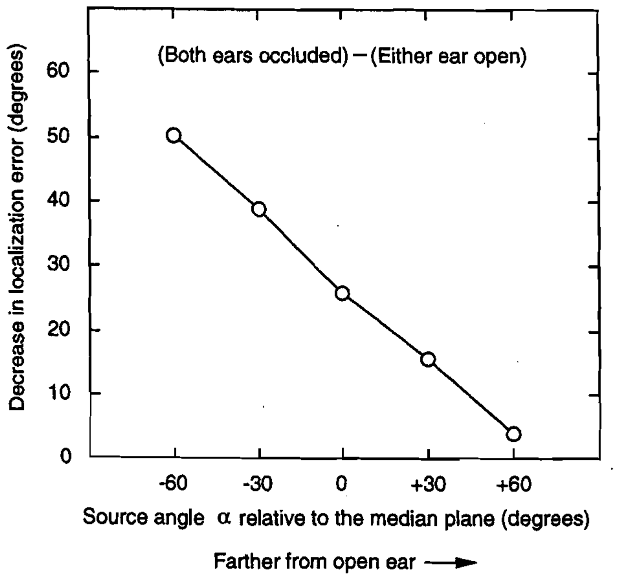

FIG. 12. Effects of either ear open on localization error. Decrease in error with either ear open relative to the both-ears-occluded condition.

In other words, the axis means how far from the occluded ear a sound source is. As a sound source shifts from the occluded ear, the increase in the error becomes small. At $+60°$, the increase is very small, as mentioned previously.

Figure 12 shows the effect of having either ear open on localization error. Here the ordinate indicates the decrease in the error when either of two occluded ears is open, relative to when both ears are occluded. In this case, plus or minus means that a sound source is on the occluded ear side or the open ear side, respectively. In other words, the abscissa indicates how far from the open ear a sound source is. As a sound source shifts from the open ear, the decrease in the error becomes small. At $+60°$, the decrease is unmeasurable, as mentioned above.

From these results, it can be inferred that the far ear no longer contributes measurably to the perception of angle β, when the shift of a sound source from the median plane exceeds 60°.

IV. DISCUSSION

Gardner (1973) investigated the effects of pinna cavities on localization ability using signals that originated in or near the horizontal plane in the anterior sector of the median plane. The result demonstrated that when the cavities of only one pinna were occluded, a considerable amount of localization ability still remained, although the localization ability was reduced compared with that achieved with no occlusion in either ear. The implication of his result was that the influence of the cavities was monaural in nature, at least insofar as localization in this sector of the median plane is concerned.

Meanwhile, the results of the present study demonstrated a significant difference in localization ability in the median plane between either ear occluded and both ears open. Moreover, the occlusion of either ear caused a significant difference in localization ability of the angle β in the saggital planes of angle $\alpha=60°$ and 120° which were outside of the median plane. Actually, the spectral shapes of input signals to the left and right ears from a sound source in the median plane are not identical which is also true in saggital planes outside of the median plane. Therefore, it is not reasonable to regard the perception of the angle β in only the median plane as a monaural phenomenon exclusively. In other words, both ears contribute to the perception of the vertical angle even n the median plane.

Musicant and Butler (1984) and Humanski and Butler (1988) investigated the contribution of the near and far ears to the localization of sound. The experimental results of both studies demonstrated unequivocally that the near ear contributes powerfully to localization accuracy. The results of the present paper support their findings. Musicant and Butler inferred that the far ear contributed, to some extent, to front–rear discrimination. This corresponds to the perception of the angle β in the present study, from the results in which there were fewer front–rear reversals when the far ear was open than when both ears were occluded. Such an inference was obtained by pooling across horizontal locations, which corresponded to the angle α in the present study. Careful observation of their results [see Table I in Musicant and Butler (1984)] indicates that, for locations close to the median plane, front–rear reversals when the far ear was open were fewer than when both ears were occluded, but that for locations far from the median plane, front–rear reversals when the far ear was open and when both ears were occluded were almost equal. Such a tendency coincides with the results of the present localization tests.

V. CONCLUSIONS

Localization tests of sound sources arranged throughout the upper hemisphere were performed in order to clarify the degree of contribution of each of two ears to the perception of angle β, that is, the vertical angle in sagittal planes.

The results confirm that: (1) Both ears contribute to the perception of the vertical angle even in the median plane, and (2) The near ear prominently contributes to the perception of angle β, as indicated by Humanski and Butler (1988). In addition, the results clarify that: (3) Not only the near ear but also the far ear contributes to the perception of angle β, and (4) As a sound source shifts laterally from the median plane, the contribution of the near ear increases, and, conversely, that of the far ear decreases. Furthermore, it can be inferred that: (5) When the deviation of the angle α of a sound source from the median plane is larger than a certain amount, the far ear no longer contributes measurably to the perception of angle β. This amount was 60° under the test conditions in the present study.

ACKNOWLEDGMENTS

The author thanks H. Aokata for his cooperation in localization tests and Y. Kuroki for her analysis for the experimental results.

APPENDIX

In order to obtain the amplitude and the phase parts of the head-related transfer function (HRTF), the pulse technique (Mellert *et al.*, 1974) was used adding 100 repetitions. This yielded an increase in the signal-to-noise ratio of 20 dB. The subject was seated in an anechoic chamber, and his head was stabilized. The tip of a probe-microphone (Brüel & Kjaer, Type 4170) was carefully set at the entrance to the auditory canal of the open ear or at the entrance of the passageway of the occluded ear. A pulse of 20 μs duration was fed through an amplifier into a loudspeaker. The probe-microphone output was led to a digital computer through an A-D converter (12 bit) with a sampling frequency of 50 kHz.

The HRTF, $H(\omega)$, is obtained by

$$H(\omega)=G(\omega)/F(\omega), \tag{A1}$$

where $F(\omega)$ is the Fourier transform of the waveform, $f(t)$, measured at the point corresponding to the center of the subject's head in a free field without a subject, and $G(\omega)$ is that measured at the entrance of the auditory canal of the open ear or at the entrance of the passageway of the occluded ear.

[1]The z-test is a test for assessing hypotheses about population means when their variances are not known and samples sizes are large ($n>100$). The test statistic z is

$$z=(\bar{x}_1-\bar{x}_2)/\sqrt{s_1^2/n_1+s_2^2/n_2},$$

where $\bar{x}_1$ and $\bar{x}_2$ are the means of sample size n_1 and n_2 and s_1 and s_2 are the sample variance. z has a normal distribution (Bethea *et al.*, 1985).

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