Free-field release from masking[a)]

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Free-field release from masking was studied as a function of the spatial separation of a signal and masker in a two-interval, forced-choice (2IFC) adaptive paradigm. The signal was a 250-ms train of clicks (100/s) generated by filtering 50-μs pulses with a TDH-49 speaker (0.9 to 9.0 kHz). The masker was continuous broadband (0.7 to 11 kHz) white noise presented at a level of 44 dBA measured at the position of the subject's head. In experiment I, masked and absolute thresholds were measured for 36 signal source locations (10° increments) along the *horizontal* plane as a function of seven masking source locations (30° increments). In experiment II, both absolute and masked thresholds were measured for seven signal locations along three *vertical* planes located at azimuthal rotations of 0° (median vertical plane), 45°, and 90°. In experiment III, *monaural* absolute and masked thresholds were measured for various signal–masker configurations. Masking-level differences (MLDs) were computed relative to the condition where the signal and mask were in front of the subjects after using absolute thresholds to account for differences in the signal's sound-pressure level (SPL) due to direction. Maximum MLDs were 15 dB along the horizontal plane, 8 dB along the vertical, and 9 dB under monaural conditions.

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INTRODUCTION

An important feature of the *binaural* system is the improvement that it affords to the detection of a signal embedded in noise relative to *monaural* listening. This improvement, which is sometimes considerably larger than can be predicted by a simple comparison of signal to noise ratios, has been termed the masking-level difference (MLD), and has been one of the most extensively studied areas of binaural hearing (for reviews, see Green and Yost, 1975; Jeffress *et al.*, 1956; Jeffress, 1972; for models of MLD, see Jeffress *et al.*, 1956; Jeffress, 1972; Hafter *et al.*, 1969; Hafter, 1971, 1977; Durlach, 1963, 1972; Colburn, 1977; Colburn and Durlach, 1978).[1]

The great majority of studies on MLDs, however, have involved earphone listening conditions. While such conditions of presentation provide better stimulus control and a much more manageable experimental environment, it is sometimes difficult to generalize the results generated to the natural listening conditions of the "real world." Free-field research, on the other hand, while not as easy to model, provides the advantage of obtaining spatial configurations that are virtually impossible to obtain with earphones. For example, a signal may be displaced from a masker along a vertical plane or perhaps in depth. In addition, the natural amalgam of interaural cues occurring under free-field listening conditions are extremely difficult to measure and faithfully reproduce under headphone conditions. It is, therefore, in the context of such differences between earphone and free-field research that free-field studies of MLD find merit.[2]

A. Free-field masking and intelligibility

Unlike earphone studies, free-field research on release from masking has thus far adopted a more practical approach. In fact, the great majority of studies conducted on free-field release from masking have been concerned with the improvements observed in speech intelligibility (Santon, 1986; Thompson and Webster, 1964; Hirsh, 1950; Plomp, 1976; Plomp and Mimpen, 1981; Kock, 1950). The general consensus has been that intelligibility increases as the masker and signal are spatially separated. These results extend to thresholds obtained for various talker–listener angles (Thompson and Webster, 1964), using pink noise or speech maskers (Plomp, 1976; Plomp and Mimpen, 1981), under reverberant or anechoic conditions (Hirsh, 1950), and for various levels and bandwidths of the masking signal (Santon, 1986).

B. Free-field masking of tones

While most of the research on free-field release from masking has concerned speech intelligibility, there are several studies that have utilized more traditional MLD signals (e.g., pure tones). Among these is the work of Santon (1987), who presented tones (0.25 to 4.0 kHz) in a background of white noise and measured detection thresholds for various positions of the masker (i.e., along the azimuth). A surprising finding was that, unlike what is observed in earphone data, detection is not necessarily poorest when the signal and masker are spatially coincident (e.g., at 1.5 kHz). Santon explains such results in terms of a model of the diffraction of sound waves around the head. This finding has also been observed by Gatehouse (1986, 1987). The effect, however, fails with broadband signals (Kurozumi and Ohgushi 1981). The largest MLD reported in these studies is in

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the order of 20 to 24 dB for low-frequency tones. However, this rather large effect is confounded by the effects of spatial location on signal to noise ratio in the ear canal and does not entirely reflect MLDs.

C. The effects of masking on free-field localization

Several researchers have asked the inverse of the above questions: How can maskers of various frequencies and spatial locations affect the *localization* function? Weis (1985), measured minimum audible angles (MAA) for tones (0.5 and 4 kHz) in the presence of bands of noise of various center frequencies (1 critical band wide) and reported that as the center frequency of the masker approached that of the target, localization performance substantially degraded. Similar results have been obtained by Harima *et al.* (1987) and Canévet (1985). Localization acuity is also degraded for nonsimultaneous presentations of signal and maskers as in forward (Canévet *et al.*, 1979) and backward (Tolkmitt, 1974) masking paradigms. Worsening of localization performance in the presence of maskers has also been noted for infants (Trehub *et al.*, 1981; Bull *et al.*, 1981).

D. The present experiments

The current experiments are divided into three studies. Study I investigates MLDs in the horizontal plane (ear level). Study II considers whether or not MLDs could be obtained along the vertical plane. The following vertical planes were considered: (1) the median vertical plane, (2) the vertical plane rotated by 45° along an azimuthal direction, and (3) the vertical plane that encompasses the aural axis. And, finally, study III explores release from masking under monaural listening condition. These experiments cover certain signal–masker configurations that have previously not been explored (e.g., vertical planes) and with fairly high resolution. Later, important subtleties will emerge in the shapes of the functions that may have otherwise gone unreported. We have, in addition, measured masked and absolute (unmasked) thresholds for most conditions both for their own merit and with the intention of at least partially accounting for the location-dependent differences in the signal–masker SPLs.

I. STUDY I: FREE-FIELD MLDs ALONG THE HORIZONTAL PLANE

A. Method

1. Subjects

Three University students served as subjects. All had extensive experience as subjects in psychoacoustic experiments including free-field studies. One subject was male, and two were female. Female subjects were instructed to use a hair clip to allow free exposure of their ears. All had normal hearing based on self-report, and each served in several practice sessions before actual data collection began.

2. Apparatus

The signal was a 250-ms click train consisting of 50-μs rectangular clicks (Wavetek, model 184) presented at a rate of 100/s (selected for their large MLD effect; Dye and Yost, 1986). All signals were checked for accuracy using a dual-channel storage oscilloscope (Tektronix model TM 506). The output of the function generators was fed through an 8-bit programmable attenuator (Coulbourn), an amplifier, and a harmonic equalizer ($\pm$ 12 dB/oct). This signal was then directed to a TDH 49 speaker in a double-walled chamber (I.A.C., model 1200). All surfaces of this chamber (including the floor and ceiling) were covered with 10.2-cm acoustic foam wedges (Sonex®, NXS-4: absorption coefficient of 0.99 for frequencies above 800 Hz). The speaker was attached to an aluminum boom (radius = 1 m) suspended from the ceiling. The output signal from this speaker was adjusted with the equalizer to produce equal power/oct (within 3 dB) over the range 0.9–9.0 kHz.

To test whether room acoustics had an effect on the signal, the speaker-mounted boom was set in motion, rotating at an angular velocity of 20°/s. A sound-level meter (General Radio) was used to measure sound levels at the center of the room.[3] With the speaker inactive, no measurable sounds were present. With the speaker active (giving a mean reading of 53.0 dBA), measurements indicated less than 0.1-dB variation as the speaker rotated through the circumference of the boom. The masking signal was broadband noise produced by a Grason–Stadler noise generator (model 901B). The output signal was directed through an amplifier, an equalizer, and to a triple-cone loudspeaker (Maxim model MX 6905) 1.6 m from the center of the boom (on the same horizontal plane as the target speaker). The output of this loudspeaker was adjusted by a harmonic equalizer to produce equal dB/oct over the range of 0.7–11.0 kHz. The level of the masker was set at 44 dBA, again, measured at the position of the subject's head.[4] When masked thresholds were measured, the masking signal was on continuously for the duration of a run. At the beginning of each run, calibration signals (from both the target and masking sources) were checked with an rms voltmeter (Hewlett–Packard, model 400 LR).

3. Procedure

Subjects were seated on a custom-made, rotating and height-adjustable chair, which was bolted to the floor of the chamber. A chin-rest extending from the lower shaft of the chair via a 1/4-in. cloth-covered steel rod was used to keep the subject's head from moving during the run. The setup is depicted in Fig. 1. The masking loudspeaker was always at the same location for study I. In order to achieve different masker locations, the subject rotated his/her position according to the following procedures. At the beginning of each run, 1 of 36 locations around the subject (10° increments) was randomly selected and the *signal* speaker was moved (by the experimenter) to that location. This speaker would remain in the same location during the entire run. One of seven light-emitting diodes (LED) would then be activated indicating the direction in which the subject should face (by rotating the adjustable chair). The seven LEDs were evenly spaced on the right side of the subject at 30° increments; subtending angles of 0°, 30°, 60°, 90°, 120°,

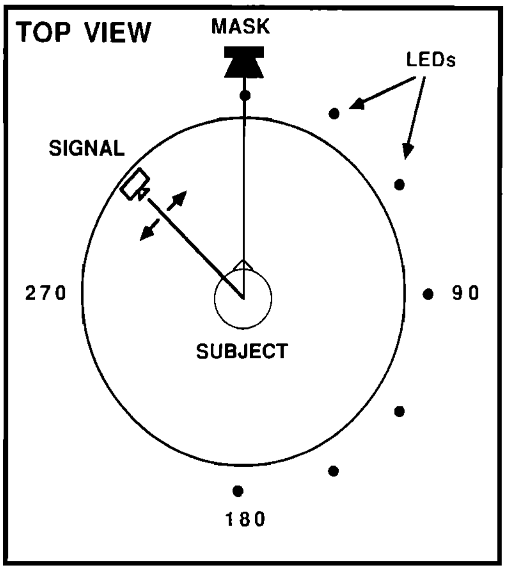

FIG. 1. Diagram of the apparatus used in study I. The masking source and the signal source were located, respectively, 1.6 and 1.0 m from the subject. The signal could rotate in a full circle around the subject. Zero deg represents the subject's front, 90° the right ear, 180° behind the subject, and 270° the left ear. Note that 0° and 360° represent the same location. The LEDs were evenly spaced at 30° increments on the subject's right.

150°, and 180° relative to the position of the masker (see Fig. 1). The subject would remain facing toward the selected LED until one threshold run for that position was completed. A two-interval, forced-choice (2IFC) two-down, one-up adaptive procedure was used (Levitt, 1971). On each trial, the LED that the subject was facing was activated for two 250-ms intervals separated by a 300-ms interstimulus interval. Concurrent with one of these two intervals, the signal was presented. The subject's task was to indicate the interval in which the sound was present. Feedback was provided for correct responses by simultaneous activation of all seven LEDs. Two correct responses in a row resulted in a decrease in level of the signal by a certain value and one incorrect response resulted in an increase in level by the same amount (tracking the 70.7% correct response level). Each threshold run consisted of 32 reversals. During the first 6 reversals, the step size was 3 dB and during the last 26 reversals it was 1 dB. The mean of the levels at the last 20 reversals was taken as the threshold for that orientation. A second LED from the remaining six was then selected and the subject was rotated so as to face this new location. The above procedure was repeated for this second location until a threshold was obtained. This procedure continued for all seven LEDs representing the seven locations. These procedures constituted one run of the experiment which yielded seven thresholds for seven spatial configurations of signal and masker. For each of the 36 runs of this experiment, a new location was randomly selected (without replacement) to which the target speaker would be moved. Again, this speaker would remain in position for the entire run. Each run lasted about 25 min. At the end of the 36 runs, thresholds had been obtained for 36 target locations and seven masker locations. A similar procedure was used to obtain absolute thresholds for 36 locations around the subject with the difference that two runs were completed for each spatial location and, therefore, each absolute threshold was based on 40 reversals.

B. Results

1. Absolute thresholds

Figure 2 presents the absolute thresholds obtained along the horizontal plane for three subjects. Each data point represents the mean detection threshold obtained at that location. Subject's front is indicated by location 0° (or 360°). Subjects' rear is at 180°, and the aural axis is represented by locations 90° and 270° (right and left, respectively). All values are referenced to the 0° condition (representing 0 dB). Error bars represent one standard error of the mean. The solid curve is a fifth-order polynomial included to facilitate visual inspection. As is evident from the figure, highest thresholds are obtained in the rear of the subjects (slightly displaced toward the left) while the lowest thresholds are obtained when the signal is slightly in front of each ear (locations 50° and 310°). This latter finding, that best detection was *not* along the aural axis (90° and 270°), is interesting, particularly when one notes that the wave fronts from these directions (50° and 310°) are roughly *perpendicular* to the surfaces of the pinna which are slightly slanted forward (approximately 4-dB advantage). The largest difference in threshold, about 10 dB, was between the rear of the subjects (+ 3 dB at 200°) and slightly in front of the two ears (− 7 dB at 50° and 310°). An analysis of variance shows a significant effect of location on thresholds [$F(35,70) = 6.03$, $p < 0.01$].

2. Masked thresholds

Figure 3 presents the mean masked thresholds for three subjects. Each panel shows results for 36 target locations and

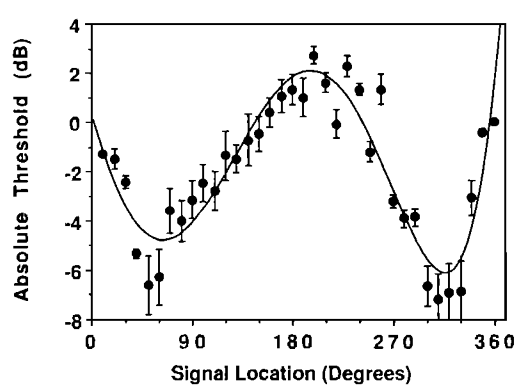

FIG. 2. Mean absolute (unmasked) thresholds obtained for three subjects as a function of 36 signal source locations. All thresholds are expressed relative to the threshold for 0° (360°). Error bars represent one standard error of the mean.

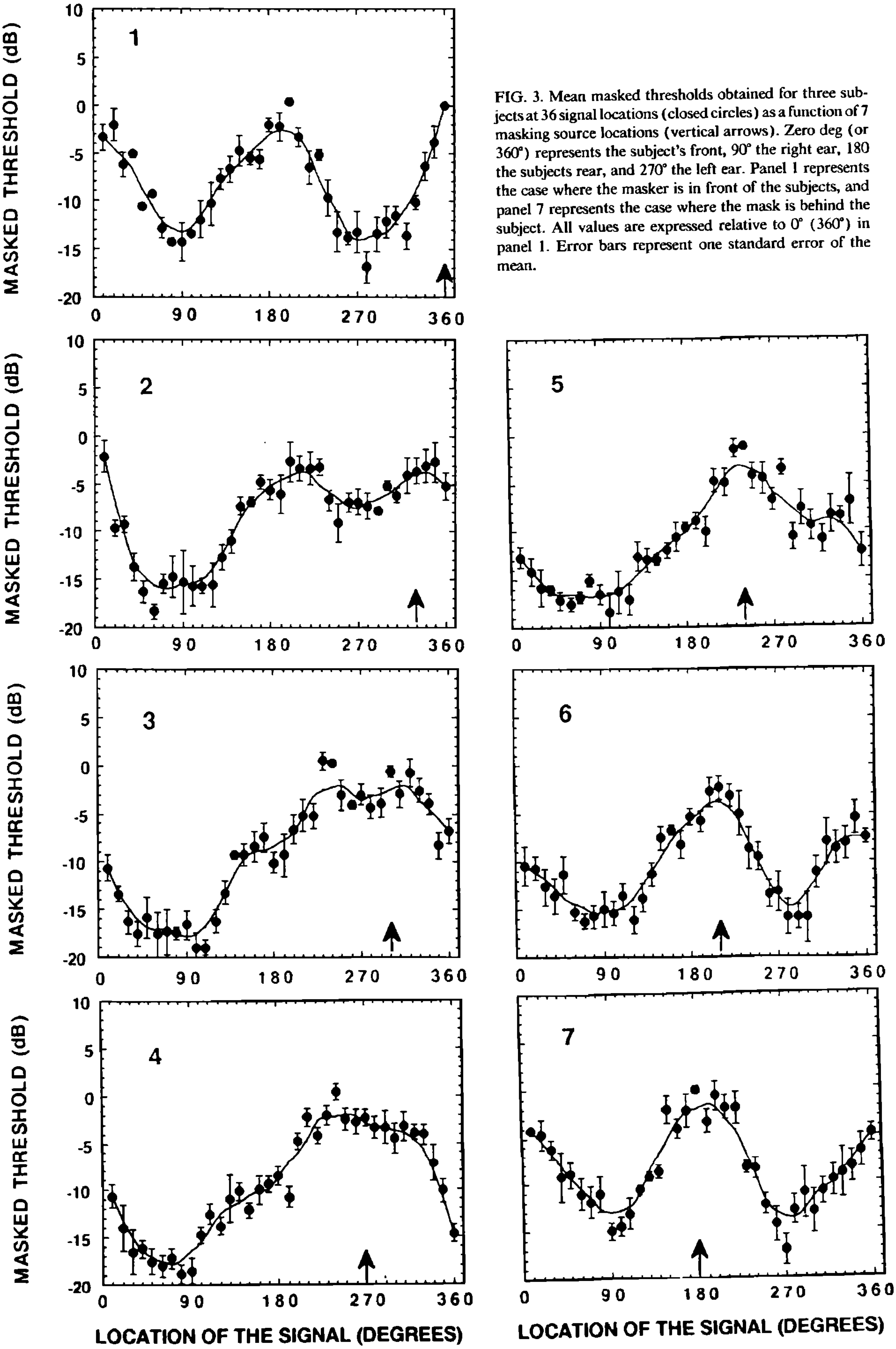

FIG. 3. Mean masked thresholds obtained for three subjects at 36 signal locations (closed circles) as a function of 7 masking source locations (vertical arrows). Zero deg (or 360°) represents the subject's front, 90° the right ear, 180 the subjects rear, and 270° the left ear. Panel 1 represents the case where the masker is in front of the subjects, and panel 7 represents the case where the mask is behind the subject. All values are expressed relative to 0° (360°) in panel 1. Error bars represent one standard error of the mean.

1 masker location. Error bars represent one standard error of the mean. The solid curves are included to facilitate visual inspection. The vertical arrows perpendicular to the abscissa represent the position of the masker in each graph. All thresholds are plotted relative to the threshold for the "straight ahead" condition where the signal and the masker are coincident and located at 0° (note that 0° and 360° represent the same locations). Again, 180° represents the condition where the signal is to the rear of the subject and 90° and 270° represent the aural axis.

The most obvious effect is that of the masker on detection thresholds as the masker is gradually moved from the front of the subjects (360°, upper left panel) to their rear (180°, lowest right panel). For the case where the masker is in front (upper left), detection thresholds are similar in form, although larger in magnitude, to those obtained when absolute thresholds were measured (Fig. 2). The main difference, however, is that, unlike what we observed for the absolute thresholds, best detection for masked thresholds was for cases in which the target was very close in azimuth to the position of the ears (about 90° and 270°), whereas, for absolute thresholds, best detection occurred at 50° and 310°. This may be partly due to the fact that the masker, which was located at 0°, may have affected the regions nearer to itself more than the further regions. This idea is further supported by the fact that thresholds under this masked condition are about equal in front and rear (if not better in the rear), while, in the case of absolute thresholds, mean threshold in front is lower than in the rear by about 2.5 dB. The largest difference in threshold observed in this condition (panel 1) is about 15 dB.

As the masking source is displaced along the azimuth toward the left ear, thresholds are correspondingly elevated for a broad region of about 40 to 50 deg around the location of the masker, while the rest of the detection function remains relatively intact. The poorest thresholds are generally obtained for conditions where the masking source and the target source are spatially coincident. As the masker is located further toward the subjects' rear (see panels 3–6) the right-hand side of the function begins to re-establish it's original form. Panel 4 represents the case where the masking source is exactly opposite the left ear (270°). Here, the largest difference in threshold is between the conditions where the signal is approximately opposite the left or right ear (90° and 270°). This difference in threshold is about 18 dB. As the location of the subject is changed relative to the masker so that the masker is exactly behind the subject (last panel), the shape of the threshold functions again resemble the function obtained for the condition in which the masker is in front (panel 1).

The largest overall improvement in performance, relative to when the signal and masker were coincident and both placed at 0°, was 18 dB for several configurations of the signal and masker (e.g., 90° in panels 3 and 4; 100° in panel 5). An analysis of variance shows a statistically significant effect of target location [$F(35,70) = 28.32, p < 0.01$] and masker location [$F(6,12) = 3.36, p < 0.05$]. There is also a significant interaction effect between target and masker location [$F(210,420) = 6.94, p < 0.01$].[5]

3. Masking level differences

A major difference between earphone studies and free-field research lies in the fact that, in the latter, as one displaces a sound source from one location to another, the signal to noise ratio is altered. For example, less energy enters the ears for a signal located behind the subject than for a signal in front. While these effects are natural components of free-field listening and should be considered accordingly, in order to compare our results with those obtained under earphone conditions, we have anchored all values to sensation levels by accounting for differences in absolute thresholds as a function of signal source direction. While this procedure may not entirely account for the advantage of one location over another (since the limiting internal and external noise are different) we have opted to adopt this procedure as a first approximation. To this end, we report here the difference between the masked threshold functions obtained in Sec. I B 2 and the absolute threshold function in Sec. I B 1.

If $D_M(\Theta)$ and $D_A(\Theta)$ represent the masked and absolute thresholds at azimuth Θ, and $D_{\text{ABS}}(\Theta)$ and $D_{\text{MASKED}}(\Theta)$ the absolute and masked thresholds relative to the thresholds at 0°:

$$D_{\text{ABS}}(\Theta) = D_A(\Theta) - D_A(0), \tag{1}$$

$$D_{\text{MASKED}}(\Theta) = D_M(\Theta) - D_M(0), \tag{2}$$

the MLD obtained at angle Θ may then be defined as

$$D_{\text{MLD}}(\Theta) = [D_{\text{MASKED}}(\Theta) - D_{\text{ABS}}(\Theta)]. \tag{3}$$

In other words, all MLDs are expressed relative to the difference between masked and absolute thresholds at 0°. The seven panels of Fig. 4 present calculations based on Eq. (3) and depict the MLD functions as the signal and masker are spatially separated. The reader should be cautious in interpreting the data from panel to panel. While the functions correctly depict the MLDs within each panel, comparison across panels cannot be made directly since changing the position of the masking source affects the signal-to-noise ratio in a similar manner that moving the signal source does.

The functions in Fig. 4, when inverted, are similar to those in Fig. 3 since lower thresholds represent larger MLDs. The functions of Fig. 4 (when inverted), however, are generally shallower than those of Fig. 3. However, this is not always the case. In some conditions, the subtraction of the absolute thresholds from the masked thresholds actually added to the magnitude of the MLD. For example, in panel 3 of Fig. 4, we see a difference in detection as large as 21 dB between 310° and 100°. This effect is larger than the largest MLD reported under earphone conditions (15 dB for $N_0S\pi$). Note that, unlike earphone data, our analog of N_0S_0 does not necessarily give the highest thresholds. When compared to this latter condition (N_0S_0), the largest MLDs are about 15 dB.

This rather large MLD (15 dB) may perhaps be accounted for by noting that, in the free field, several cues may work in conjunction with one another. As with earphone studies, the subjects may use interaural temporal (onset–ongoing) and intensive information (Hafter, 1977) available from the displacement of the singal along an azimuth. In

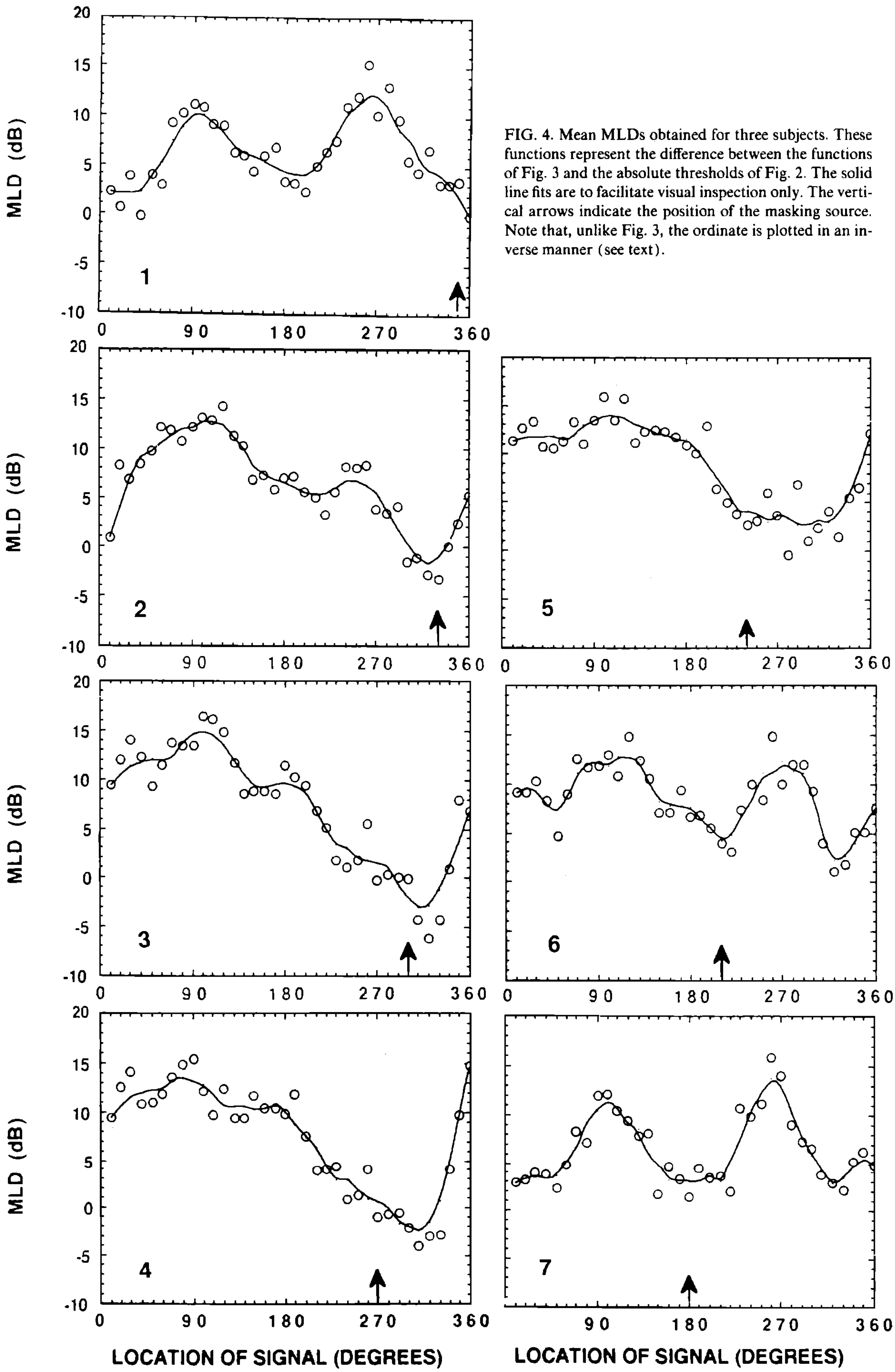

FIG. 4. Mean MLDs obtained for three subjects. These functions represent the difference between the functions of Fig. 3 and the absolute thresholds of Fig. 2. The solid line fits are to facilitate visual inspection only. The vertical arrows indicate the position of the masking source. Note that, unlike Fig. 3, the ordinate is plotted in an inverse manner (see text).

addition, however, unlike headphone listening conditions, there are monaural and binaural spectral cues available from the interactions of the signal with the pinna and the head (Butler *et al.*, 1990; Searle *et al.*, 1975).

An analysis of variance test on the transformed data of Fig. 4 indicates significant effects for signal location [$F(35,70) = 8.93$, $p < 0.01$], masker location [$F(6,12) = 3.34, p < 0.05$], and the interactions of these two variables [$F = (210,420) = 6.95, p < 0.01$] on the obtained MLDs.

II. STUDY II: FREE-FIELD MLDs ALONG VERTICAL PLANES

Traditional earphone experiments have been restricted to the study of MLDs along a lateral dimension in intracranial space. Free-field research, however, is free of such constraints and it is therefore capable of investigating release from masking for such cases as the vertical plane. Free-field studies of MLDs have, until now, confined their work to the horizontal plane. The vertical plane, however, provides a number of interesting conditions. Variations in elevation on the median plane, for example, allows spatial separation between target and masker without substantially altering the available interaural cues. The latter condition is important since models of MLD have relied heavily on these interaural cues to explain release from masking (Durlach, 1963). The following experiments were conducted to explore such effects along vertical planes.

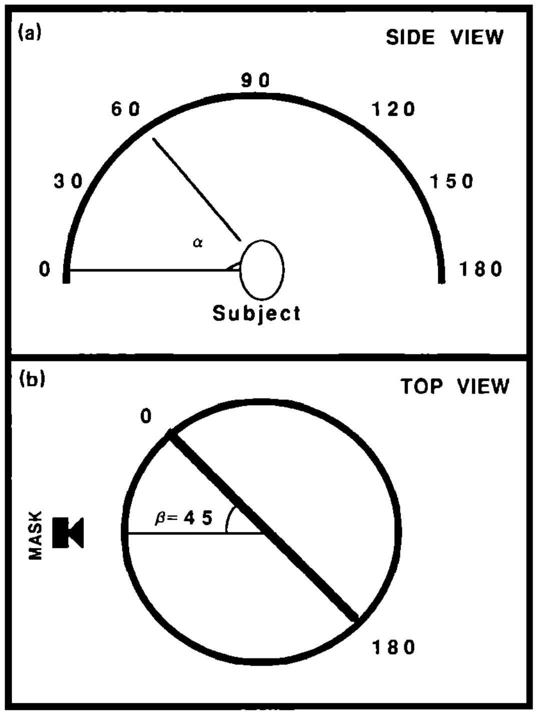

FIG. 5. (a) A side view of the setup in study II (vertical). This figure depicts the location of the signal source along the median vertical plane (Sec. II B 1). Zero deg represents subject's front, 90° above the subject's head, and 180° behind the subject. (b) A top view of the setup in Sec. II B 2 (study II). The line extending through 0 and 180 depicts the vertical plane rotated in the azimuthal plane by 45°. Subject is facing the masking source; α represents vertical displacement and β represents horizontal displacement.

A. Method

1. Subjects and apparatus

The subjects and apparatus were the same as in study I.

2. Procedure

All procedures were similar to those used in study I, with the following changes. The masking source was always located at 0° in the horizontal plane relative to the subject for all conditions. The target source was displaced along one of three vertical planes. The first was the median plane. Seven target locations were used. These included 0° (on the horizontal plane), 30°, 60°, 90° (above the subject's head and perpendicular to the horizontal plane), and 120°, 150°, and 180° (again, back on the horizontal plane but behind the subject). Figure 5(a) depicts these seven target locations (angle alpha). The target was displaced along a circular arc (1 m in radius) on the vertical plane. In addition, two other vertical planes were examined: (1) the vertical plane that cut through an azimuth of 45° and (2) the vertical plane that encompasses the aural axis (azimuth of 90°). The latter is of particular interest since maximum variations in interaural cues would be available. Figure 5(b) depicts the first of these two conditions (45° azimuth). In Fig. 5(b), angle β represents the azimuthal displacement of the vertical plane.

During each run, one of the three vertical planes was randomly selected and the boom was moved so that its vertical arc would be encompassed by the desired plane. The boom remained in this position during the entire run. The subject always faced the masking source that was located at an azimuth of 0°. At the beginning of the run, one of the seven LEDs that corresponded to one of the seven vertical target locations was activated. The subject moved the target speaker to that location. He/she then returned to the 0° position and initiated the beginning of the run by pressing one of the response keys. The LED located at 0° was then activated and the 2IFC task was conducted at this position. After a threshold was obtained at this location, a second LED was activated indicating where the subject should place the target speaker next. The subject then returned to his/her initial location (0°) and repeated the procedure. Using this method, seven thresholds (for seven target locations) along the same vertical plane were collected during a single run. Absolute thresholds were also obtained for all conditions using a similar procedure.

B. Results

1. MLDs along the vertical plane at 0° azimuth (vertical median plane)

The three panels of Fig. 6 present the results for the median vertical plane ($\beta = 0°$ azimuth). The data are the mean for three subjects. Error bars represent one standard error. All thresholds are expressed relative to those for 0° azimuth, 0° vertical condition. The top panel shows the absolute thresholds. The middle panel shows the masked thresholds. The third panel shows the difference between the first two panels (i.e., MLD). Again, as was evident on the horizontal plane (Fig. 2), absolute thresholds are generally lower in the front than in the rear. Highest thresholds were observed for the 150° condition (i.e., 30° elevated from the rear of the subject). Performance improves, although slightly, as the target returns to the horizontal plane (180°). The largest difference in threshold occurs between 30° and 150° (about 5 dB). It is noteworthy that the difference in absolute thresholds between 0° and 180° (2.5 dB) is similar to the difference in absolute thresholds for the same configurations in the horizontal plane depicted in Fig. 1 (about 2 dB).

Masked thresholds (panel 2) decrease as the target is displaced vertically, reaching a minimum at 60° elevation. Highest thresholds occur for targets located at the same elevation as the masker (0° and 180°). This is of interest since the absolute thresholds (top panel) show the inverse of this result; performance is best for no-elevation conditions. The largest difference in masked threshold (7.5 dB) occurs between 180° (rear of subject on the horizontal plane) and 60° (front of subject elevated by 60°).

Panel 3 shows the MLDs (i.e., difference between the functions of top and middle panels). This function resembles panel 2 (middle), with the difference that the locus of best detection has shifted toward the rear of the subject (from 60° elevated in front to about 120° elevation in the rear). This effect is about 7.5 dB.

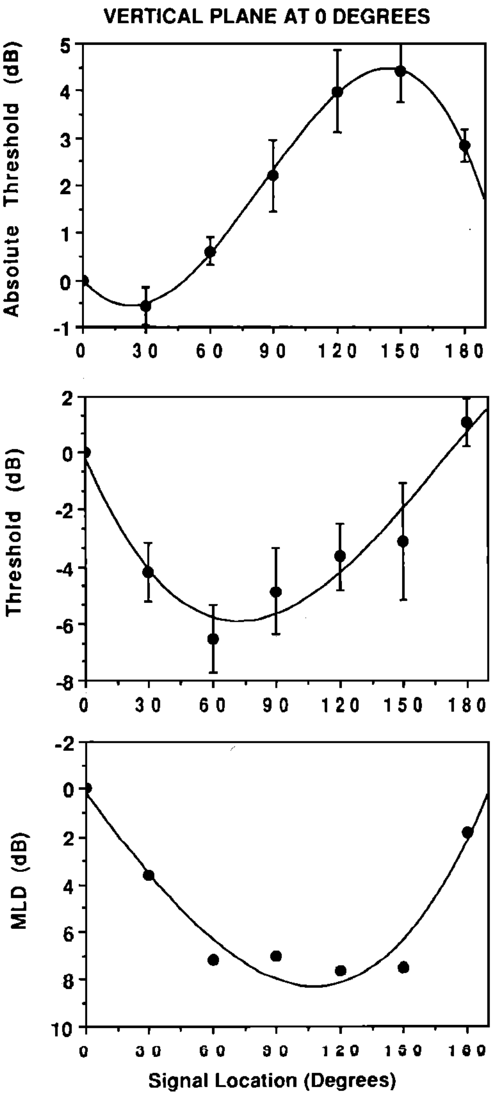

FIG. 6. Top panel presents the mean absolute (unmasked) thresholds obtained for three subjects along the vertical median plane. Zero deg is in front of the subject, 90° is above the subject's head, and 180° is back on the horizontal plane, but behind the subject. The middle panel represents the masked thresholds obtained along the same plane. The masking source was located in front of the subject and at ear level. All values are referenced to 0° horizontal and vertical. Bottom panel presents the difference between the masked and absolute thresholds. This is the function obtained after signal-to-noise ratios have been accounted for. Error bars represent one standard error of the mean.

2. MLDs along the vertical plane at 45° azimuth

The three panels of Fig. 7 present the thresholds obtained along the vertical plane rotated by 45° along the azimuth. The data are the mean for three subjects. Error bars represent one standard error. All values are expressed relative to thresholds obtained at 0° elevation, 0° azimuth (study II: Sec. II B 1). Absolute thresholds are lowest when the target is in front and on the horizontal plane (0° elevation).

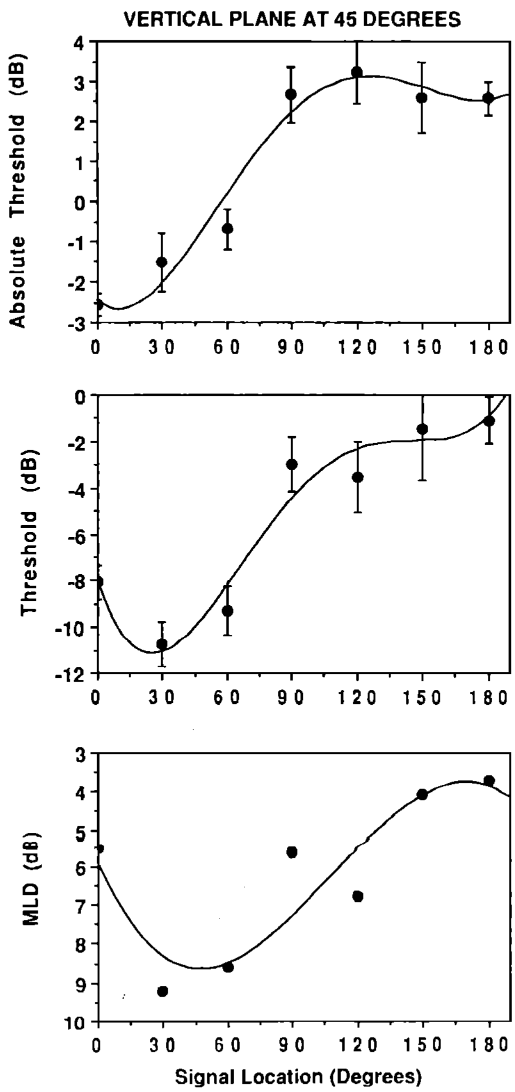

FIG. 7. Same as Fig. 6 but for a vertical plane rotated in the azimuthal direction by 45° [panel (b) of Fig. 5].

Detection gradually worsens as the target is moved vertically along this plane. Poorest performance is observed as the target moves toward the rear of the subject. From 90° (above the subject's head) to 180° (back on the horizontal plane), absolute thresholds are fairly similar. The largest difference in threshold (about 6 dB) is observed between the 0° elevation (i.e., at 45° azimuth) and 120°.

The lowest masked threshold (middle panel) is observed when the target was elevated by 30°. Thresholds increase markedly as the target is moved above the subject's head and increases slightly as it continues to move toward 180° (back on the horizontal plane, 225° azimuth). The largest difference in masked thresholds is between 30° elevation and 180° (vertically) at an azimuth of 45° (10 dB). The largest MLD (bottom panel) is about 6 dB.

3. MLDs along the vertical plane at 90° azimuth

Figure 8 presents the data along the vertical plane that incorporates the aural axis (rotated in the azimuth by 90°). Zero deg in this case represents the target signal located on the horizontal plane and opposite the right ear, 90° represents the location of the target when it is above the subject's head, and 180° represents the condition where the target is back on the horizontal plane but opposite the left ear. The masking source is located at 0° azimuth in front of the subject. The symmetrical nature of these data is expected since the conditions going from 0° to 90° vertical are the mirror image of the conditions for 180° to 90°. Absolute thresholds are lowest when the signal is elevated by 30° and 150°, and are highest when the signal is above the subject's head. The largest difference in absolute threshold in this condition is about 6 dB (between 90° and 150°). The highest masked thresholds (middle panel) are also observed above the subject's head (90°). However, lowest thresholds are obtained along the horizontal plane (at 0° and 180°). The largest difference in threshold in this condition is 8 dB (between 90° and 180°). The MLDs vary in a similar way to masked thresholds. The largest difference in MLD was about 7 dB (bottom panel). The case where the signal is exactly above the subject's head is interesting since it is common to all three conditions of study II. The thresholds obtained for this condition (both absolute and masked) are, as expected, similar.

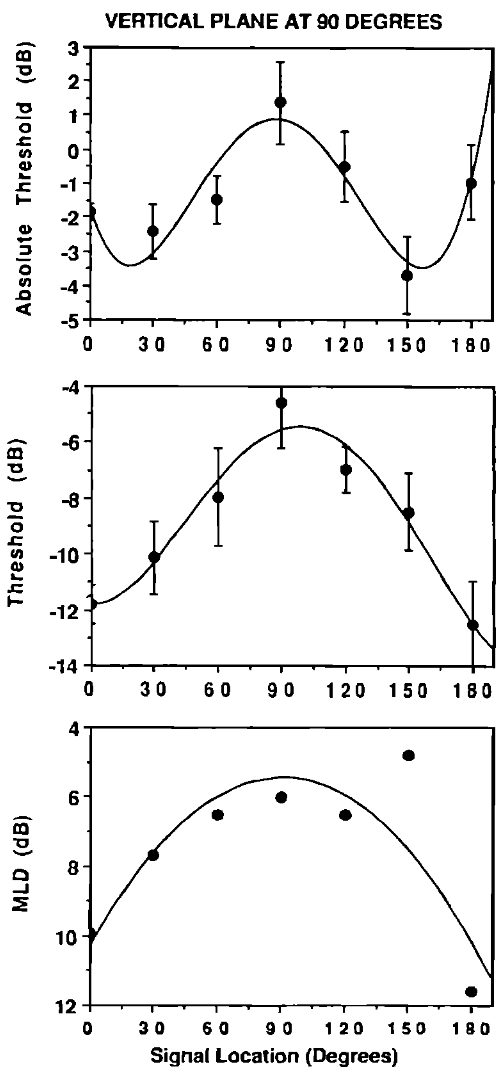

FIG. 8. Same as Fig. 6 but for a vertical plane rotated in the azimuthal direction by 90° (encompassing the aural axis).

An analysis of variance indicates a significant effect of: (1) signal location [$F(6,12) = 10.91, p < 0.01$], orientation of the plane [$F(2,4) = 9.93, p < 0.05$], and their interactions [$F(12,24) = 2.62, p < 0.05$] for the *absolute* thresholds and (2) signal location [$F(6,12) = 3.73, p < 0.05$], orientation of the plane [$F(2,4) = 37.29, p < 0.01$], and their interactions [$F(12,24) = 12.69, p < 0.01$)] for the *masked* thresholds.

III. STUDY III: FREE-FIELD MLDS UNDER MONAURAL CONDITIONS

Masking-level difference (MLD) has traditionally referred to improvements in the detection of masked signals under binaural relative to monaural listening conditions (Jeffress *et al.*, 1956). The various models of MLDs (Jeffress *et al.*, 1956; Jeffress, 1972; Durlach, 1963, 1972; Hafter, 1971, 1977; Colburn, 1977) have interpreted release from masking in terms of changes in interaural disparities at the two ears. One such model, the lateralization model, proposes that one is able to better detect a signal with an interaural disparity different than that of the masker's, simply because the signal is heard at a different location (Hafter, 1977). This argument is interesting since it would suggest that release from masking may be observed in the absence of interaural cues providing a change in location is sensed. In study II we did, in fact, observe an 8-dB release from masking under such a condition (vertical median plane). While one may argue that small interaural disparities may be present along the vertical plane (Searle *et al.*, 1975), such disparities are probably too small to fully account for the observed release from masking. A more reasonable explanation may be that subjects are capable of utilizing the direction-dependent dips and peaks in the power spectrum, perhaps as a form of profile analysis (Green, 1988).

A second condition in which one may perceive a change in spatial location of a sound without utilizing interaural disparities is under monaural conditions (Butler, 1975).

The cue to monaural *localization* is the direction-dependent change in the power spectrum of the signal in the ear canal (Shaw, 1974; Butler *et al.*, 1990). Release from masking under such conditions is of interest in terms of expanding the notions and models of release from masking since monaural listening under earphone conditions has usually been considered as the referent anchor to binaural conditions. A major difference between earphone and free-field studies of MLD, however, is that there are virtually an infinite number of monaural signal–masker configurations in the free field that have but one analog under earphone listening.

Previous work on monaural release from masking using speech signals (Hirsh, 1950; Plomp, 1976) has demonstrated an improvement in intelligibility as the masker and signal are spatially separated. However, this improvement (as in the binaural case) can, at least, partially be attributed to changes in signal-to-noise ratios as the signal is moved from one location to another. Study III was conducted to investigate whether subjects could, as is hypothesized with vertical release from masking (study II), use pinna-shaped spectral patterns to improve the detection of a signal in noise.

A. Method

1. Subjects

Five University students served as subjects. Two were experienced in psychoacoustical experiments and three were experimentally naive. All were given practice runs to ensure their understanding of the task before data collection began. Female subjects were instructed to use a hair clip to allow free exposure of their ears. All subjects had normal hearing based on self-report.

2. Apparatus and procedure

The apparatus and procedures were the same as in studies I and II with the following changes. To ensure monaural listening, the procedure described below was followed for each subject at the beginning of the experiment. A soft ear plug (Cabot corporation) was inserted into the cavities of *both* ear canals. In addition, shooting gallery ear protectors were worn over both ears. The subject was, thus, effectively "deafened" at both ears for moderate level sounds. The masking speaker was placed at 50° azimuth (i.e., where best unmasked binaural thresholds had been reported). The subjects had direct control over the intensity of this sound by pressing on either a left key (increase level) or right key (decrease level). Subjects were instructed to change the level of the masking speaker until the sound became just inaudible. The level of the masker was then reduced further (by the experimenter) by 6 dB. The level of the masker was kept constant at this value during the entire experiment. The value was different for each subject but generally about 45 dBA as measured at the position of the subject's head. For the monaural runs, the right ears for all subjects remained blocked, while the plugs and ear covers were removed from the left ears.

3. Conditions

The coordinates were as follows: 0° represented subject's front, 90° represented the subject's right (occluded ear), 180° represented the subject's rear, and 270° represented the subject's left ear (open ear).

The target–masker configurations were as follows. (1) On the side of the open ear (Fig. 9): (a) signal speaker and noise speaker, spatially coincident and located at 0°. This condition is denoted by N_0S_0. (b) Noise at 0° and signal at 270° (N_0S_{270}). (c) Noise at 270° and target at 0° ($N_{270}S_0$). (d) Noise at 270° and target at 270° ($N_{270}S_{270}$). (2) On the side of the occluded ear (Fig. 10): (a) Noise at 0° and signal at 90° (N_0S_{90}). (b) Noise at 90° and signal at 0° ($N_{90}S_0$).

For most configurations, data were collected under monaural *and* binaural conditions for the purposes of comparison and under masked *and* unmasked conditions.

B. Results

1. On the side of the open ear

Figure 11 shows the data for the conditions depicted in Fig. 9. The top panel shows the absolute thresholds obtained at 0° and 270° for both binaural and monaural conditions. These values are expressed relative to the threshold for the binaural condition at 0° (binaural S_0), which is therefore not shown (0 dB). Since there was no masking source involved, there are only two cases shown here. One can observe small differences (less than 2 dB) between the monaural and binaural absolute thresholds for each condition.

Panel 2 (bottom) of Fig. 11 shows the masked thresholds. Again, all thresholds are expressed relative to that for the binaural condition at 0°. There were no significant differences between the monaural and binaural conditions for the first three cases [panels (a) to (c) of Fig. 9]. For the condition depicted in panel (d) ($N_{270}S_0$), however, the binaural condition yielded thresholds about 10 dB lower than for the monaural condition. Compare the monaural thresholds in this case with the monaural threshold in N_0S_{270}. This latter

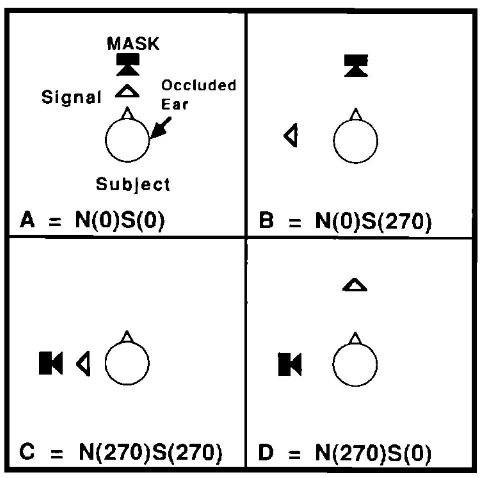

FIG. 9. The four conditions of Sec. III A (study III) concerning events on the side of the open ear.

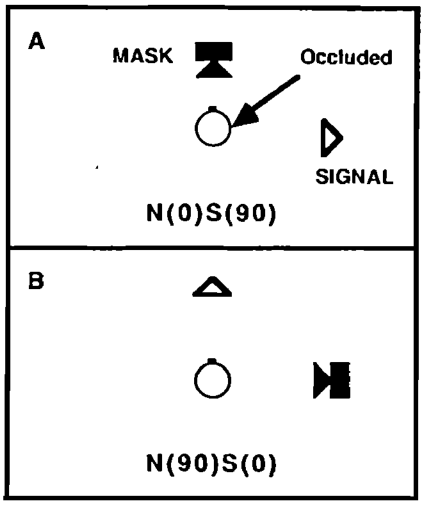

FIG. 10. The two conditions of Sec. III B (study III) concerning events on the side of the occluded ear.

case is the inverse of the former. This comparison suggests that interchanging the positions of the signal and masker results in a 15-dB shift in threshold. This large effect can be better understood by comparing this figure to Fig. 9 of Shaw (1974), which depicts the sound-pressure transformations from free field to the eardrum. Under what we have termed the $N_{270}S_0$ (90° in Fig. 9 of Shaw), if we restrict our calculations to the 5- to 7-kHz region, the spectrum level of the signal (at 0°) at the eardrum is between 5 to 10 dB greater than the free-field measurements would indicate. In the same frequency region, however, the spectrum level of the masker (at 90°) is at least 15 dB greater than free-field measurements. Thus, given that the free-field spectrum levels of masker and signal are equivalent, the sound pressures developed at the eardrum are about 7.5 dB greater for noise than for the signal in $N_{270}S_0$ in this frequency region. The opposite, of course, would be true when the location of masker and signal are reversed (N_0S_{270}). Therefore, the difference in signal-to-noise ratio between $N_{270}S_0$ and N_0S_{270} is about 15 dB in the frequency region between 5 and 7 kHz. If detection is based on this frequency region, then we would expect a 15-dB difference in masked threshold between these two conditions. This is indeed what we observe in the present experiment.

An analysis of variance was also performed on the data indicating a significant effect of signal–mask conditions [$F(3,12) = 40.26, p < 0.05$], monaural–binaural conditions [$F(1,4) = 14.76$, $p < 0.05$], and their interactions [$F(3,12) = 46.86, p < 0.05$].

2. On the side of the occluded ear

Figure 12 presents the data for the two conditions depicted in Fig. 10. Unlike Sec. IV A, data were collected only under monaural conditions. Absolute thresholds were also collected only for the condition depicted in panel (a). For the situation shown in panel (b), absolute thresholds were available from Sec. A. All masked thresholds are expressed relative to the *binaural* N_0S_0 threshold obtained in Sec. IV A. All absolute thresholds are expressed relative to the *binaural* S_0 absolute threshold. Note that the solid and hatched bars in Fig. 12 represent masked versus absolute thresholds, while in Fig. 11, they represent binaural versus monaural thresholds. As can be seen, both masked and absolute thresholds for condition A (N_0S_{90}) are substantially elevated compared to the N_0S_0 condition. Compare this condition (Fig. 12, left bars) to the case depicted in panel (b) of Fig. 9 (Fig. 11, lower panel, N_0S_{270}). The only difference here is that the target is moved from the side of the open

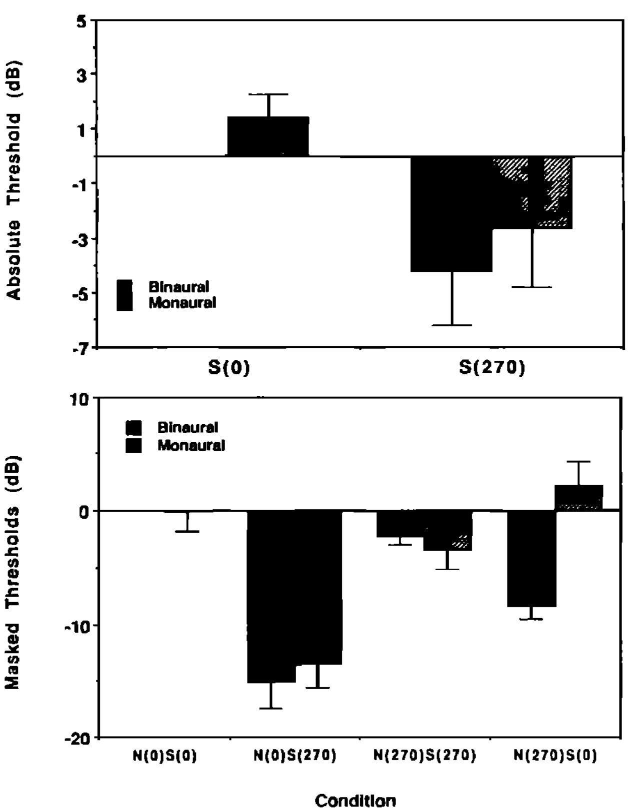

FIG. 11. Results of the conditions depicted in Fig. 9. Top panel shows absolute thresholds under binaural and monaural conditions. These values are expressed relative to the absolute binaural thresholds obtained in front of the subjects (S_0). Bottom panel shows masked thresholds expressed relative to the binaural condition at 0° [therefore, this latter condition is not shown (far left)]. Error bars represent one standard error.

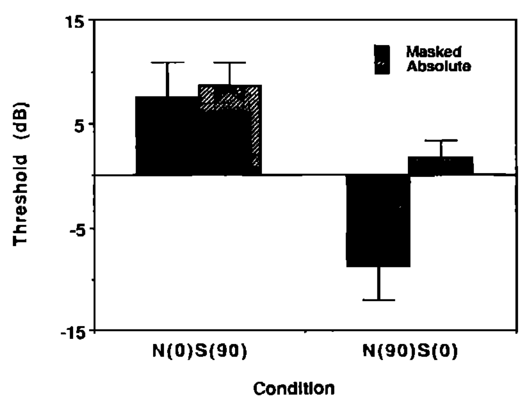

FIG. 12. Results of the conditions shown in Fig. 10. Note the difference between the parameters in this figure (masked/absolute) and Fig. 11 (binaural/monaural). Error bars represent one standard error.

ear to the side of the occluded ear. The advantage gained by by-passing head shadow effects on the signal is over 20 dB. For condition (b), Fig. 10, in which the masking source is now at the side of the occluded ear, masked thresholds are approximately 8 dB lower than N_0S_0. Compare this case to condition (d) of Fig. 9 (monaural). Monaural thresholds in condition (d) are higher by about 10 dB. An ANOVA test indicates a significant effect of signal–masker configuration [$F = (1,4) = 116.89, p < 0.05$].

3. Monaural MLDs

As in studies I and II, in order to account properly for variations in signal-to-noise ratios, absolute thresholds for each configuration were subtracted from masked thresholds. Note that, since the position of the masking source also affects the signal-to-noise ratio, we have restricted our calculations to the three conditions where the masking source was in front of the subject. These are N_0S_0, N_0S_{90}, and N_0S_{270}. All values are expressed relative to the *monaural* N_0S_0 condition and therefore this case is not depicted (see Fig. 13). The purpose of expressing thresholds in terms of the monaural condition (and not the binaural) was to observe the magnitude of the MLDs resulting purely from a change in the relative locations of the target and masker. Note, however, from the bottom panel of Fig. 11 that the binaural and monaural thresholds for the N_0S_0 condition are practically identical. An advantage of about 9 dB can be observed in the N_0S_{270} condition (Fig. 13). This advantage, as stated above, cannot be attributed to signal-to-noise ratios. An ANOVA indicates a significant effect of signal–masker conditions [$F(2,8) = 22.71, p < 0.01$].

IV. GENERAL DISCUSSION

In most studies using speech or broadband signals (e.g., Kurozumi and Ohgushi, 1981), thresholds have been found to be poorest when the signal and masker are spatially coincident (along the horizontal plane). MLDs for click trains (present study) are generally larger than for speech signals (Hirsh, 1950). We did not observe for clicks what has been reported for tones, namely, that spatial coincidence does not necessarily yield the poorest detection for some frequencies (Gatehouse, 1987). No previous data on the vertical plane are available.

The *magnitudes* of the MLDs we have obtained on the horizontal plane resemble those obtained under earphone listening conditions with tones (15 dB maximum). However, compared to earphone MLDs reported for clicks (Dye and Yost, 1986), we have obtained values significantly larger (by about 9 dB). This is probably due to the fact that in the cited study, only interaural differences in time were present, while, under free-field conditions, several cues (e.g., intensity, time, spectral cues) may be utilized. For some free-field situations, where detection is inferior to N_0S_0, the overall difference in threshold between the poorest and best conditions may be as large as 21 dB (Fig. 4, panel 3). This is different from the reported findings of earphone studies that diotic (N_0S_0) configurations provide the poorest detection thresholds. MLDs obtained along the vertical plane (8 dB) and under monaural conditions (9 dB) are smaller than those along the horizontal plane.

To demonstrate the complexity of free-field listening, we have combined some of the horizontal and vertical data (i.e., masked thresholds) in the three-dimensional plot of Fig. 14. Note that this figure represents *only* the situation where the masking source is in front of the subject (360° horizontal and 0° vertical). Certainly, one would obtain different results for any other positioning of the masking source. The *x* axis represents the location of the signal along the horizontal. As in previous cases, 360° (or 0°) represents the subject's front, 180° represents the subject's rear, 90° the right ear, and 270° the left. The *z* axis represents the vertical position of the signal. Zero degree represents ear level, and 90° is straight above the subject's head. The *y* axis (vertical) depicts *masked* thresholds in dB. All values have been expressed relative to 0° (or 360°) horizontal and 0° vertical (0 dB). We have interpolated where necessary.

While substantial research has been conducted on MLDs under earphone listening, there has been little attempt to integrate this research with free-field data. How can the models of MLD, for example, fit in the context of "real world" listening? Earphone research suggests that most interaural disparities (e.g., time, intensity, etc.) produce some degree of release from masking compared to no disparities (Jeffress *et al.*, 1956). This is particularly true when the auditory system is able to process the signal as a unified image. For example, if there are significant spectral or temporal inconsistencies in the signal at the two ears, the corresponding auditory image will seem diffused. One can observe the effect of fusion on masking by noting that, when noise is correlated at the two ears, the masking effect for the S_0 condition is larger by about 3 dB than when the noise presented to each ear is independent of the other (Egan and Benson, 1966).

An interesting question, however, arises in the case of release from masking along the vertical *median* plane. How can MLDs occur in the absence of interaural information? It is reasonable to assume that the reason one obtains release

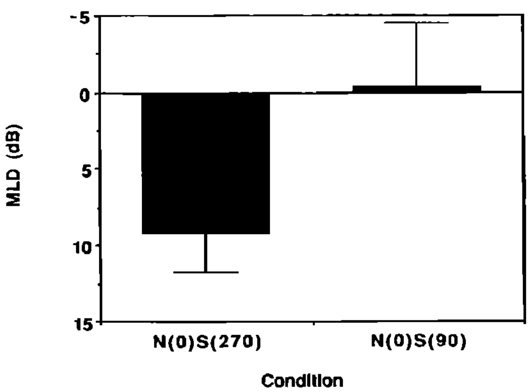

FIG. 13. Release from masking under monaural conditions after signal-to-noise ratios have been corrected for. Each bar represents the mean monaural masked threshold obtained for three subjects less the monaural absolute thresholds at each location. Both values are expressed relative to the *monaural* N_0S_0 condition.

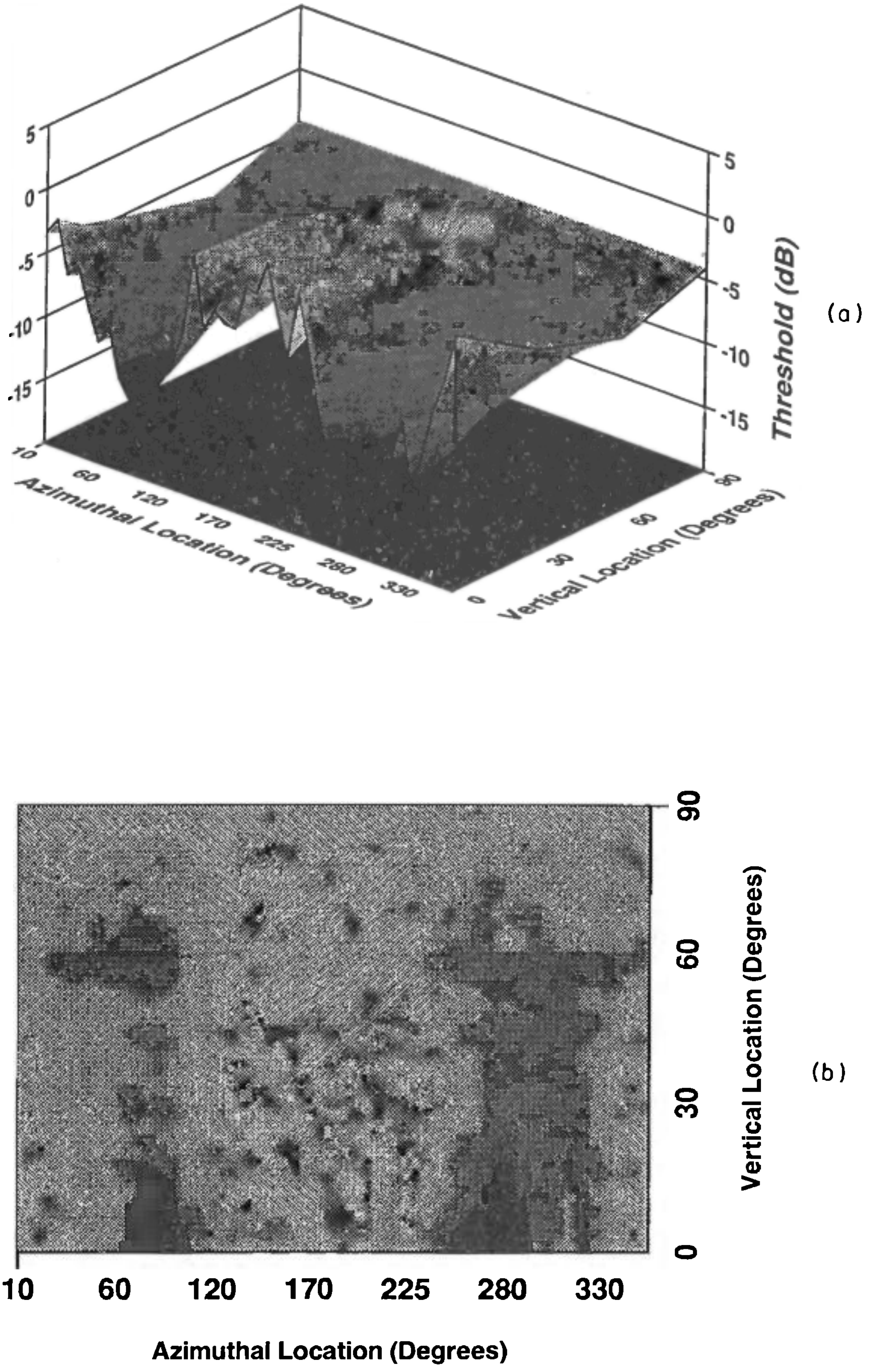

FIG. 14. (a) Mean masked thresholds for a masking source located at 0° (360°) horizontal and 0° vertical relative to the subject in three-dimensional auditory space. The *x* axis represents the signal location along the horizontal plane, the *z* axis the signal location along the vertical plane (e.g., 90° is above the subjects head), and the *y* axis (vertical) the masked thresholds. (b) Top-down view of (a). Darker areas represent areas of best detection.

from masking along the vertical median plane (or under monaural conditions) is the ability of subjects to utilize direction-dependent peaks and troughs in the power spectrum resulting from the interactions of the stimulus with the convolutions of the pinna. When the masker and signal are at the same location, they are similarly filtered. When they are in different locations, certain frequencies of the masker are attenuated, while the same frequencies in the target may be amplified (probably in the regions of 4 to 8 kHz; Khun, 1987, 1983; Shaw, 1966, 1974; Sivian and White, 1933). A profile analysis (Green, 1988) of the resultant pattern of spectral differences is most likely *one* cue to improved detection.

A second plausible cue is the increase in the signal-to-noise ratio at the level of specific auditory filters. Figure 13 from Mehrgardt and Mellert (1977) provides the free-field to ear-canal-entrance transfer functions for different elevations on the median plane. As the signal is elevated to about 85°, the signal-to-noise ratio in the 5 to 10-kHz region increases by about 8 dB while it falls by 3 to 6 dB in the 1.5 to kHz. Wightman and Kistler (1989) provides similar results for the transfer functions at the eardrum. If detection is based on the 5 to 10-kHz regions, providing that the upward spread of masking does not affect this region, then the change in signal-to-noise ratio here can account for the difference in detection.

The process by which release from masking occurs on the vertical is, of course, at least partially (if not entirely), different than that involved in horizontal MLDs (particularly under earphone conditions). The major MLD cues in the horizontal are, as we noted, interaural differences of time and intensity (Hafter, 1977), and in the free-field, perhaps some spectral shaping (low pass filtering) resulting primarily from head shadows and torso reflections (Khun, 1987). The spectral shaping in the vertical plane is probably at higher frequency regions than in the horizontal since most of the filtering is produced by pinna convolutions (Butler, 1975; Butler *et al.*, 1990; Mehrgardt and Mellert, 1977) and not head shadows.

In addition to spectral shape discrimination, another potential candidate for an effective monaural cue is the change in signal-to-noise ratio at the level of individual filters. Consider the N_0S_{270} case in Fig. 11. Compare this condition to what is observed in Fig. 9 of Shaw (1974) at 90° and 0°. This positioning of signal and noise produces a greater monaural signal-to-noise ratio in the 5- to 7-kHz region (by about 8 dB) than when signal and noise are both located in front of the listener (N_0S_0). Therefore, we would expect a monaural release from masking under the N_0S_{270} condition. If we consider this condition with the right ear open (binaural), in addition to this 8-dB advantage in signal-to-noise ratio at the left ear, standard dichotic cues also become available. Therefore, we might expect larger unmasking in the binaural configuration, which is indeed observed (15 dB). It is important to note, however, that the 8-dB postulated advantage (Shaw, 1974) does not fully account for the obtained monaural thresholds (about 13 dB). The difference between this latter larger advantage and the 8-dB advantage predicted from Shaw, we speculate, may be attributed to the additional cross-filter comparisons (i.e., profile analysis). This idea is also supported by the thresholds obtained in Fig. 13 where absolute thresholds have been accounted for. Thus, either the profile of the signal or detection at specific frequency regions may be responsible for improved detection. We cannot say with certainty which of these two may account for the difference in threshold (for either the vertical or monaural cases). The monaural data of Study III, as we noted, suggests that even if we look at the level of individual filters there is still 5 dB of unmasking unaccounted for. In addition, for the vertical plane condition, when the signal is elevated to about 90°, there is substantially more energy at the lower frequency regions, perhaps partially capable of remotely masking the higher frequencies in the signal. Thus, the profile of the signal is probably a viable cue in the observed improvements in detection under monaural and perhaps vertical conditions. However, we do not have a definitive answer on this.

While it is also possible that a third candidate cue, binaural pinna disparities (Searle *et al.*, 1975), may account for some of the release from masking along the vertical plane, this is less likely to be a major cue compared to the signals profile and variations in the signal-to-noise ratios at specific frequency regions. At least the monaural data seem to indicate such.

Another example of the direction dependency of cues is provided by the case where the signal is in front and the noise at the side (Fig. 11; $N_{270}S_0$). In this latter condition, there is a smaller signal-to-noise ratio at almost all frequencies relative to the baseline condition where both the signal and noise are in front (Shaw, 1974). Therefore, one would expect more masking in this condition than in the monaural N_0S_0. Indeed, this is what occurs and a disadvantage of 2 dB is obtained. If the right ear is now freed to make listening binaural, then dichotic cues become available and we would expect to observe further release from masking. This is exactly what occurs (7 dB).

VI. CONCLUDING REMARKS

From the standpoint of theory, we believe that such release from masking resulting from discrimination between spectral shapes (both under monaural and vertical plane conditions) or from the direction dependency of signal-to-noise ratios at specific frequency regions, is as viable as release based on binaural phase or intensity cues. Consider, for comparison, the case of sound *localization* and its related mechanisms. There are, in sound localization, other than binaural time phase and intensity coding, dimensions that are indispensable to our consideration of spatial hearing, for example, those of vertical localization (Saberi *et al.*, 1991; Perrott and Saberi, 1990; Saberi and Perrott, 1990) and distance perception (Mershon and Bowers, 1979; Mershon and King, 1975; Stryble and Perrott, 1984). Emphasis of research in spatial hearing on lateralization paradigms (i.e., binaural time-intensity cues), however, has not confined our notion of localization to binaural paradigms. We would like to argue similarly for the mechanisms of release from masking. There is evidence both for and against the notion that masking-level differences are intimately related to the mechanisms of sound localization (Hafter, 1977; Hafter *et al.*, 1973; Henning, 1974; Wightman and Green, 1971). We have seen, in our experiments, some evidence in support of a relation between these two. The models of the MLD have, primarily, been associated with interpreting data obtained under headphone listening conditions. It seems reasonable, however, to assume that in an attempt to emulate stimulus settings in free-field environments (Wightman and Kistler, 1989; Blauert, 1989) and for a more complete understanding of unmasking and its related mechanisms, that earphone research should account for such complex free-field observations. It is our sincere hope that the present paper will stimulate such research.[6]

ACKNOWLEDGMENTS

We would like to thank David M. Green, Brian C. J. Moore, Ervin R. Hafter, Robert A. Butler, and two anonymous reviewers for their many helpful comments on earlier drafts of this paper.

[1] The largest release from masking under earphone listening is for the condition in which the signal (usually a low-frequency sinusoid) is 180° out of phase at the two ears while the masker remains in phase (N_0S_π). The N_0S_0 threshold is usually taken as the referent condition in MLD studies since it equals thresholds obtained under monaural conditions. The improvement under the N_0S_π condition relative to the N_0S_0 is about 15 dB. Other signal–mask configurations have included different signal phase disparities (Hirsh and Burgeat, 1958; Jeffress *et al.*, 1956), interaural intensive (Colburn and Durlach, 1965; Zerlin, 1966), temporal (Flanagan and Watson, 1966; Yost and Dolan, 1978), and frequency differences (Robinson, 1971) and various other complex signal configurations (Mcfadden, 1987; Moore, 1988).

[2] The term MLD has usually been associated with earphone studies. Partially because the more extensive research on the topic has involved earphone studies, and partially because the original discovery of the effect was with headphones. In the study of speech intelligibility the term speech reception threshold (SRT) is usually employed. Other researchers (Gatehouse, 1987) have used the term MLD in free-field studies of release from masking with tones. In the present study, we have decided that the term MLD is appropriate, mostly to extend the notions of MLD to more natural environments (i.e., free-field research). Clearly, there are some differences and similarities between the two and an argument can favor either their independence or integration.

[3] The boom was rotated by a computer controlled motor located outside the chamber. No audible or measurable motor sounds were present while the boom was in motion. A complete description of this system is presented in Perrott and Tucker (1988). To measure sound intensities, a 0.5-in. microphone was suspended in the center of the room where the subject's head would be positioned during testing. The output cable of this microphone was directed to the adjacent control room.

[4] This low intensity was selected to prevent temporary threshold shifts from long-term exposure to the masking signal.

[5] For purposes of documentation to a known referent, the mean (unreferenced) absolute threshold obtained at 0° was 5.2 dB (A-weighted) and the mean (unreferenced) masked threshold obtained at N_0S_0 (panel 1 of Fig. 3) was 31.7 dB (A-weighted).

[6] All raw and transformed individual and mean data are available by request on Macintosh, IBM, or hardcopy format.

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