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Weber's law, the "near miss," and binaural detection

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Weber functions (ΔI/I in dB) for gated 250-Hz tones were studied for monaural and several binaural stimulus configurations (homophasic, and antiphasic with varying phase angle for addition of signal to masker). The various cues for discrimination of signal plus masker from masker alone are functions of intensity increments at one or both ears, an intensity increment at one ear coupled with a decrement at the other, or the introduction of a phase difference between the ears. The decline of the Weber fraction with increasing masker level (the "near miss" to Weber's law) was confirmed for monaural discrimination over the entire 40-dB range, and a similar rate of decline was found for various binaural stimuli over the lower half of that range. The data also confirm the individual differences found in other studies for sensitivity favoring either interaural amplitude or interaural phase shifts.

The Weber function for monaural intensity discrimination of tone bursts provides an interesting and important deviation from Weber's law. McGill and Goldberg (1968a, 1968b) have highlighted the problem, calling it the "near miss" to Weber's law, and have shown how it may reflect the compression role of the transduction of stimulus energy (E) to neural counts ($\bar{n}$) by the transform $\bar{n} = aE^p$. Using I for stimulus intensity and ΔI for the magnitude of its just discriminable (energy) increment, the fact that empirical plots of ΔI in dB against I in dB are well fitted by linear functions with slopes of about .90 (the near miss), rather than 1.00 (Weber's law), means that the exponent of the power transform (p) is about .20 rather than unity.

Given our understanding of monaural and binaural processes, Schacknow and Raab (1973), reporting confirmation of the monaural near miss for several test frequencies, and Yost (1972), reporting confirmation of Weber's law for homophasic and antiphasic binaural tones, appear to contradict each other. With homophasic tones, the listener receives identical inputs at the two ears, and it is commonly assumed that detection or discrimination mechanisms for that configuration are the same as for monaural listening. Indeed, careful examination of the two papers shows that they did use stimulus parameters that were almost identical, except for duration and range of I. Schacknow and Raab include data for 250-Hz tones of 250 msec duration with 10-msec rise/fall times. The Weber function slope of about .90 was confirmed for a 40-dB range of I. Yost studied 250-Hz tones of 128 msec duration with 10-msec rise/fall times. Weber's law was apparently confirmed for a 12-dB range of I. (Yost did not raise the question of the near miss.) The results of Schacknow and Raab were presented as ΔI/I in dB SL, while Yost's results were presented as (I + ΔI)/I in dB SPL. Adjusting for absolute threshold would place the Yost data well within the intensity range studied by Schacknow and Raab. Yost may have missed the near miss because his range for I was too small. (Indeed, for one of the two subjects of Schacknow and Raab, the near miss is clear in the data for 30 and 50 dB SL and for 50 and 70 dB SL, but, for the other subject, ΔI/I is nearly constant for 30 and 50 dB SL and then drops between 50 and 70 dB SL.)

We decided to reinvestigate the Weber function for the 250-Hz tone bursts of Schacknow and Raab, but this time for the several binaural configurations studied by Yost as well as for monaural listening. The clarification of the binaural and monaural results are of theoretical importance for the following reasons. Binaural theory (Hafter, 1971; Jeffress, 1972) presumes that the detection of tone masked by tone (the discrimination of pure-tone intensity levels) depends on *interaural differences* in intensity and/or phase for antiphasic listening, which may do their work by shifting the apparent location of the tone image within the head. For the antiphasic conditions of interest here, the masker (standard) is interaurally in-phase (M0), but the signal to be detected is interaurally phase-shifted by π radians (Sπ), and the two are added together with some relative phase difference (α). Clarification of this M0Sπ configuration is made as usual in Figure 1, in which the phase-angle difference for addition, α, is defined at one ear and is,

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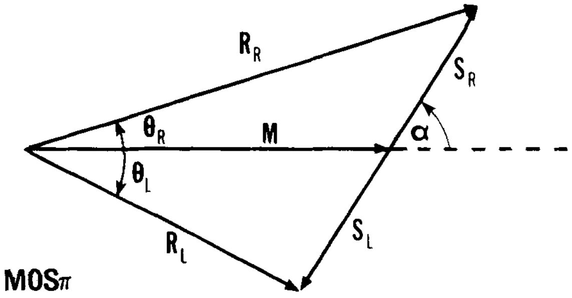

$$I = M^2$$
$$\Delta I = S^2 + 2MS\cos\alpha$$
$$I + \Delta I = R_R^2$$
$$\Delta I/I \text{ (dB)} = 10 \log\left[(S^2 + 2MS\cos\alpha)/M^2\right]$$
$$(I + \Delta I)/I \text{ (dB)} = 10 \log(R_R^2/M^2)$$
$$\Delta\theta = \theta_R + \theta_L$$
$$\Delta R = 10 \log(R_R^2/R_L^2)$$

Figure 1. Vector diagram showing the antiphasic MOSπ stimulus configuration and definitions of relevant derived quantities. M is the amplitude of the masker at either ear, S_R and S_L are the signal amplitudes for right and left ears, α is the phase angle of addition of signal to masker (defined for the right ear), R_R and R_L are the resultant vector sums at the respective ears, and θ_R and θ_L are the respective phase shifts that result from the addition of the signal to the masker. For the monaural MmSm or the homophasic M0S0 stimulus configurations, only the right-ear portion of the diagram is applicable, since there are no resultant interaural differences.

therefore, $\pi - \alpha$ at the other. For homophasic binaural detection, when the interaural phase shift is 0 for both masker and signal, M0S0, detection is presumed to be based on the intensity increment at either ear (it is the same at both ears) that results from the addition of signal to masker.

Many studies, including Yost's (1972), confirm that the increment required for antiphasic detection depends on α and may become considerably smaller than that for homophasic or monaural detection (the binaural advantage) as α departs from 0. (Such antiphasic increments are, in fact, generally much too small for monaural detection.) Consequently, we had expected intensity discrimination for tones to follow the near miss for monaural and homophasic listening. For antiphasic listening, we had no clear expectations. (Yost predicted Weber's law for M0S0, but could not make any predictions for M0Sπ.) If Weber's law fails in antiphasic listening and a near miss is found, explanations such as those advanced for monaural mechanisms may be incorrect (or at least not unique). It could be that Weber functions are different for different values of α as well. Except for the small monaural changes of amplitude resulting from addition of the signal to the standard, only interaural intensity differences exist for α = 0 radians, only interaural phase differences exist for $\alpha = \pi/2$ radians, and both exist for intermediate values of α. Weber's law for $\Delta I/I = 10 \log[(R_R^2 - M^2)/M^2]$ implies, and is implied by, the independence of M of each, the interaural phase difference, $\Delta\theta = \theta_R + \theta_L$, and the interaural amplitude ratio, $\Delta R = 10 \log(R_R^2/R_L^2)$ (see Figure 1), and our results will also be examined in terms of these variables. In a sense, we wished to clarify, for tone-on-tone masking, whether intensity increments, interaural intensity differences, and interaural phase differences lead to different departures from Weber's law.

METHOD

The psychophysical procedure and method of data reduction were fairly similar to those of Yost (1972). Subjects self-paced trials for blocks of 40 trials each. The paradigm for each trial was 2ATFC (two-alternative temporal forced choice) and consisted of a 1,200-msec waiting period, followed by two observation intervals separated by 550 msec, and then a response interval that was terminated by the subject's vote (buttonpress). Both masker and signal were binaural or monaural 250-Hz tone bursts originating from the same oscillator.[1] The masker was presented in both observation intervals (except for absolute threshold determinations). The signal was added to the masker in one of the two observation intervals, with equal probability for each. In each interval, the masker alone or the sum of signal and masker was gated for a 250-msec total duration with 10-msec rise/fall times.[1] Indicator lights were used to mark the observation intervals and to provide trial-by-trial feedback regarding correct or incorrect decisions. For each block of trials, all stimulus parameters, including signal level, were fixed. Listening was done over TDH-39 earphones in an IAC double-walled soundproof chamber. For any stimulus configuration, signal levels were varied in 2-dB steps over different blocks to generate psychometric functions, and this was replicated four times. Data for different stimulus configurations were collected in a balanced order, except that absolute thresholds were determined first, in order to set masker sensation levels. For each subject and for each stimulus configuration and signal level, the four replications were treated as one data set. For each such data set, the proportion of trials for which the subject correctly decided that the signal was in the first interval and the proportion of trials for which the subject incorrectly decided that the signal was in the first interval were used as hit and false-alarm rates. Then the two corresponding standard normal scores were determined, and $1/\sqrt{2}$ times their sum was used as d'. A linear psychometric function of the form $\log d' = c + k \log S^2$ (Egan, Lindner, & McFadden, 1969) was fitted by least squares to the data over levels of S. Intercepts for d' = 1 were used as thresholds (corresponding to a maximum proportion correct of .76).[2] Slopes of the Weber functions were determined from least squares fitted straight lines for plots of thresholds in the form ΔI/I (dB) vs. I (db SL).

The stimulus conditions studied included S0 for signal only (absolute threshold determinations) and those for determinations of resultant increment ($R_R^2 - M^2$) thresholds: MmSm for monaural listening and the M0S0 and M0Sπ configurations for binaural listening, with α of M0Sπ at 0, $\pi/4$, and $\pi/2$ rad.[1] Levels of the masker (standard) were set to 30, 50, and 70 dB SL for each subject. After a reasonable amount of practice, the entire procedure was run for four subjects, including one of the authors (H.T.). It was then replicated for M0S0 for five masker levels, for three of those subjects.

RESULTS AND DISCUSSION

For ready comparison with the tabulated results of Schacknow and Raab (1973) and the graphed results of Yost (1972), all of our results are presented for individual subjects and as averages over subjects in two forms. In terms of the vector diagram of Figure 1, the Weber fraction, ΔI/I in dB, is computed as $10 \log[(R_R^2 - M^2)/M^2]$ and $(I + \Delta I)/I$ in dB is computed as $10 \log(R_R^2/M^2)$. Signal levels at absolute threshold, Weber fractions as ΔI/I, and slopes of intensity discrimination functions for our tone bursts are displayed in Tables 1, 2, 3, 4, 5, and 6, for our individual subjects.[3] Our discussion is organized with regard to these tables. To help visualization of various trends of our results and facilitate comparison with Yost's results, our data are transformed into plots of (I + ΔI)/I as a function of I in Figures 2-7.

Table 1
Weber Fractions (ΔI/I, in Decibels) and Slopes of Intensity Discrimination Functions for Monaural Stimuli

		Masker Level (in Decibels SL)			
Subject	ABT	30	50	70	Slope
Z.C.	25.0	−4.2	− 7.2	− 8.8	.89
C.H.	34.6	−7.5	−11.3	−10.9	.82
T.I.	32.5	−2.3	− 6.6	− 8.3	.85
H.T.	29.9	−6.2	− 7.8	−10.3	.90
Average	30.5	−4.7	− 7.9	− 9.5	.88

Note–ABT = absolute binaural threshold in decibels SPL.

Table 2
Weber Fractions (ΔI/I, in Decibels) and Slopes of Intensity Discrimination Functions for Homophasic Binaural Stimuli

	Masker Level (in Decibels SL)			
Subject	30	50	70	Slope
Z.C.	−12.1	−10.7	−10.7	1.04
C.H.	− 8.7	−12.3	− 7.5	1.03
T.I.	− 5.8	−10.6	− 6.9	.97
H.T.	− 9.1	− 9.7	− 8.6	1.01
Average	− 8.4	−10.7	− 8.2	1.01

The values of signal power for absolute binaural thresholds (Table 1) averaged 30.1 dB SPL. Since our signal duration was .25 sec, this compares well with the binaural S0 measurements for 1-sec tone bursts at 250 Hz obtained by Diercks and Jeffress (1962), which averaged 27.5 dB SPL. (The average energy of our tone bursts was 3.4 dB less than theirs.)

Conditions With No Interaural Cues

For monaural listening (MmSm), every individual listener clearly confirms the finding reported by Schacknow and Raab (1973) with respect to both the magnitudes of the Weber fractions and the slope of the Weber function (Table 1). There is a near miss to Weber's law for monaural listening, with a slope very close to .90.

The slopes for the homophasic (M0S0) results come very close to unity. However, examination of the data reveals that Weber's law is not so simply confirmed. The functions are concave upwards, with the changing slopes passing through unity near the midrange of M. The average trend is supported by three of the four subjects (Table 2). Our replication for five intensity levels (Table 3) confirms the minimum near 50 dB SL. The average trend is shown by all three subjects. If the absolute thresholds of subjects in the Yost (1972) study are similar to ours, then expressing his data in sensation level would place it at just about the minimum of our Weber function. Since his data were averaged across subjects with respect to sound pressure level, individual threshold differences and the shorter range for M could have led to his flattened average Weber function.[4]

Our U-shaped functions were fitted with straight lines separately for the range 30-50 dB SL and the range 50-70 dB SL (Table 3). A homophasic near miss to Weber's law does appear, as a slope of no more than .90, below 50 dB SL. Above that level, there is another near miss to Weber's law, but in the opposite direction; the slope is greater than 1.10.

The most obvious subjective cue for intensity discrimination is loudness, and it may be questioned whether or not the binaural summation of loudness has somehow influenced our Weber functions. Abso-

Table 3
Weber Fractions (ΔI/I, in Decibels) and Slopes of Intensity Discrimination Functions for Homophasic Binaural Stimuli (Replication)

	Masker Level (in Decibels SL)					Slope		
Subject	30	40	50	60	70	30-70	30-50	50-70
Z.C.	−6.1	−11.4	− 9.8	− 8.9	− 8.0	.99	.82	1.09
C.H.	−8.8	−10.4	−13.6	−10.0	−10.0	.98	.76	1.18
H.T.	−8.3	− 8.7	−11.9	−10.2	− 8.5	.98	.82	1.17
Average	−7.6	−10.1	−11.5	− 9.7	− 8.8	.98	.81	1.14

Table 4
Weber Fractions (ΔI/I, in Decibels) and Slopes of Intensity Discrimination Functions for Antiphasic Binaural Stimuli

	Masker Level (in Decibels SL)			
Subject	30	50	70	Slope
Z.C.	−4.2	− 3.7	−3.3	1.02
C.H.	−8.8	−10.2	−8.5	1.01
T.I.	−3.0	− 6.2	−4.7	.96
H.T.	−4.7	− 7.3	−8.3	.91
Average	−4.8	− 6.4	−5.7	.98

Note—α = 0 radians.

Table 5
Weber Fractions (ΔI/I, in Decibels) and Slopes of Intensity Discrimination Functions for Antiphasic Binaural Stimuli

	Masker Level (in Decibels SL)			
Subject	30	50	70	Slope
Z.C.	−10.1	− 9.5	− 8.4	1.04
C.H.	−11.3	−12.3	−10.5	1.02
T.I.	− 9.5	− 9.3	− 9.4	1.00
H.T.	−11.6	−12.8	−12.7	.97
Average	−10.5	−10.7	−10.0	1.01

Note—α = π/4 radians.

Table 6
Weber Fractions (ΔI/I, in Decibels) and Slopes of Intensity Discrimination Functions for Antiphasic Binaural Stimuli

	Masker Level (in Decibels SL)			
Subject	30	50	70	Slope
Z.C.	−17.0	−19.8	−20.6	.91
C.H.	−17.8	−23.0	−23.8	.85
T.I.	−14.1	−16.6	−18.3	.90
H.T.	−22.9	−30.2	−30.8	.80
Average	−17.0	−20.2	−21.5	.89

Note—α = π/2 radians.

lute thresholds for binaural listening are only about 3 dB less than those for monaural listening. Loudness generally grows at a faster rate in binaural than in monaural hearing, but the slope of the line relating the paired sensation levels over an 80-dB range exceeds .90 (Reynolds & Stevens, 1960; Treisman & Irwin, 1967). Thus, we expect our binaural levels for 30 to 70 dB SL to be equivalent ("matched") in loudness to monaural levels less than 10 dB more intense. The monaural near miss is seen to hold from about 25 to almost 80 dB SL for 1,000-Hz tones in McGill and Goldberg (1968a, 1968b). This, then, leaves our result unexplained. (Nevertheless, the McGill and Goldberg near miss does exist at lower levels for homophasic stimuli.) Additional argument against a simple explanation of intensity discrimination in terms of loudness cues appears when comparing the values of the monaural and homophasic increment thresholds (Tables 1, 2, and 3). The comparison reveals a homophasic advantage at 50 dB SL or less, while at 70 dB SL discrimination is clearly better if only one ear is involved. This is an unexpected result in the face of the reported nature of binaural loudness summation. Clarification of the problem would require a study of binaural-monaural loudness matching for the stimuli used in our experiment.[5]

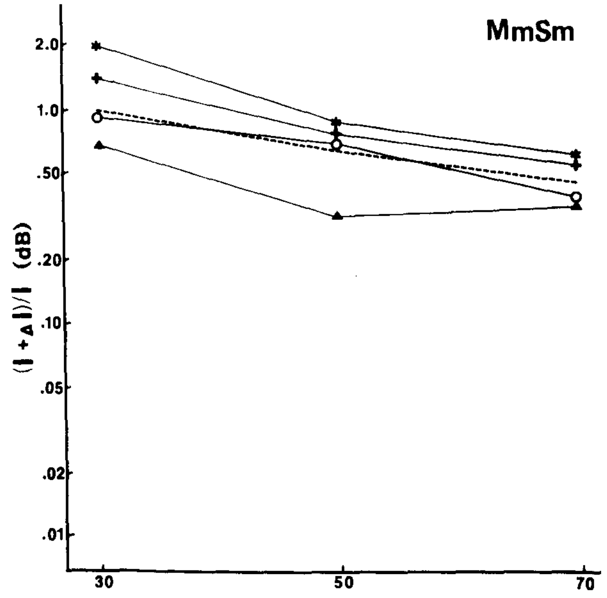

Figure 2. Values of (I + ΔI)/I in dB vs. I in dB SL for the monaural condition MmSm (derived from Table 1). The symbols are results for individual subjects (+, Z.C.; ▲, C.H.; *, T.I.; O, H.T.). The dashed line is the average over these subjects. For this and all subsequent figures, note that the ordinate is logarithmic.

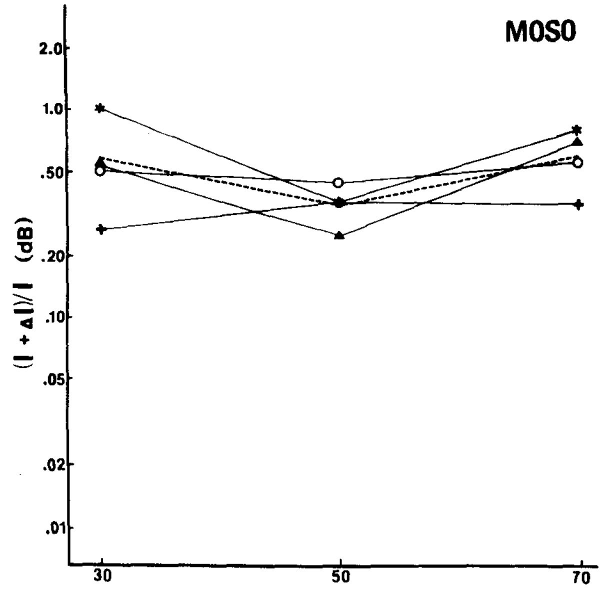

Figure 3. Values of (I + ΔI)/I in dB vs. I in dB SL for the binaural condition MOSO (derived from Table 2). The symbols are results for individual subjects (+, Z.C.; ▲, C.H.; *, T.I.; O, H.T.). The dashed line is the average over these subjects.

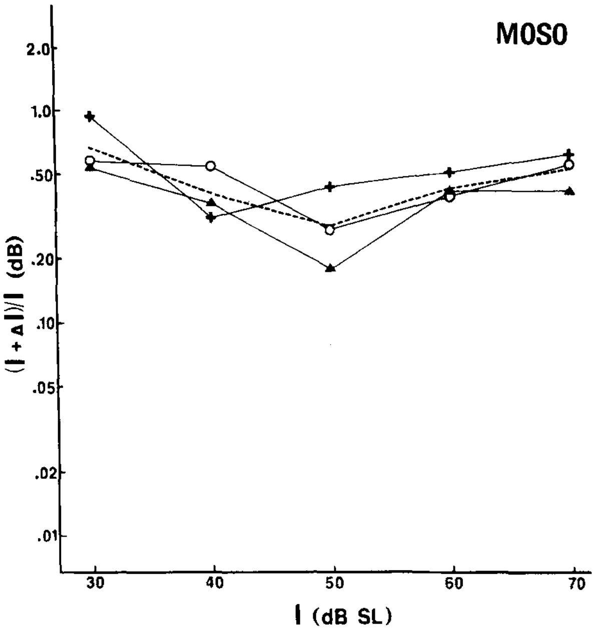

Figure 4. Values of (I + ΔI)/I in dB vs. I in dB SL for the binaural condition M0S0 (derived from Table 3). The symbols are results for individual subjects (+, Z.C.; ▲, C.H.; *, T.I.; ○, H.T.). The dashed line is the average over these subjects.

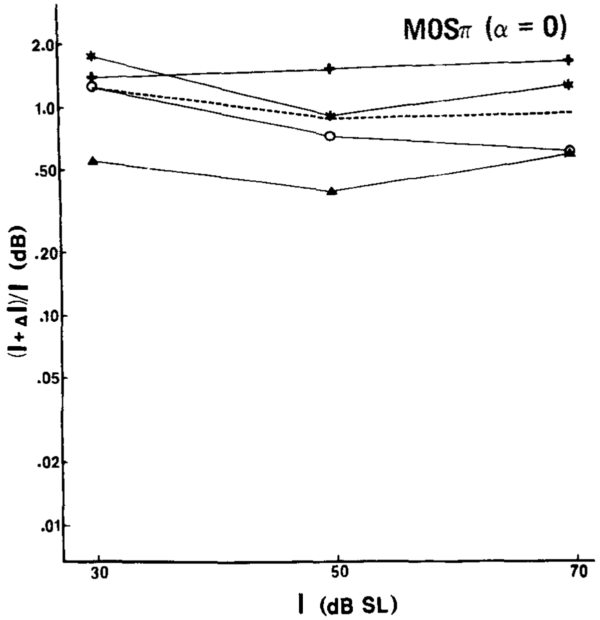

Figure 5. Values of (I + ΔI)/I in dB vs. I in dB SL for the binaural condition M0Sπ, $\alpha = 0$ rads (derived from Table 4). The symbols are results for individual subjects (+, Z.C.; ▲, C.H.; *, T.I.; ○, H.T.). The dashed line is the average over these subjects.

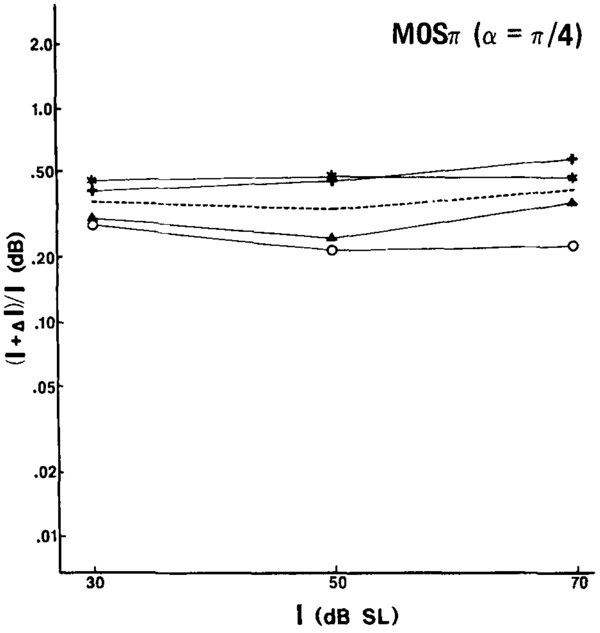

Figure 6. Values of (I + ΔI)/I in dB vs. I in dB SL for the binaural condition M0Sπ, $\alpha = \pi/4$ rads (derived from Table 5). The symbols are results for individual subjects (+, Z.C.; ▲, C.H.; *, T.I.; ○, H.T.). The dashed line is the average over these subjects.

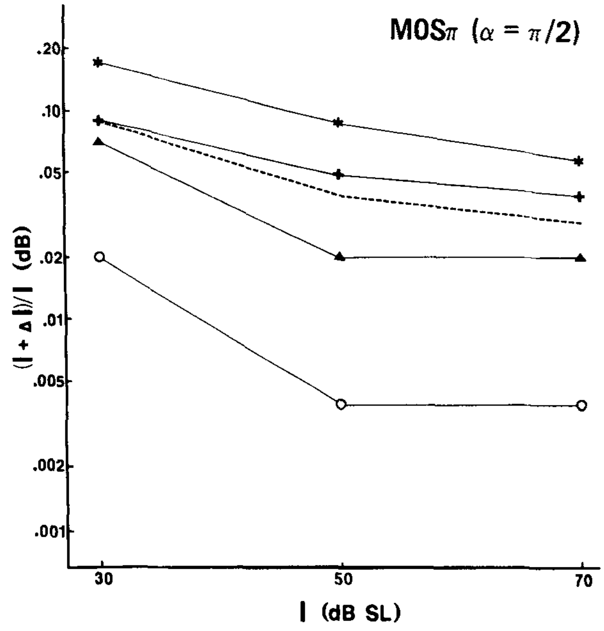

Figure 7. Values of (I + ΔI)/I in dB vs. I in dB SL for the binaural condition M0Sπ, $\alpha = \pi/2$ rads (derived from Table 6). The symbols are results for individual subjects (+, Z.C.; ▲, C.H.; *, T.I.; ○, H.T.). The dashed line is the average over these subjects. Note the shift in range of the ordinate in this figure as compared with those in previous figures, reflecting the greater discriminability achieved in this case of antiphasic listening.

Conditions With Interaural Difference Cues

The subjective sensation associated with discrimination for antiphasic stimuli is invariably reported to be a shift in the lateral position of the subjective image. Nevertheless, following our line of thought in terms of ΔI/I, the results for antiphasic (M0Sπ) listening (Tables 4, 5, and 6) show some interesting features. For $\alpha = 0$ rads, each of three subjects appears to perform as close to Weber's law as for homophasic listening. Only one, H.T., shows a slope near .90. However, the Weber function is also U-shaped for C.H. and T.I., with slopes close to .90 for the lower region. That interaural intensity discrimination and homophasic intensity discrimination may involve the same mechanism is supported by the fact that these three subjects are the same ones showing the U-shaped Weber functions for M0S0.[6] For $\alpha = \pi/4$ rads, three subjects do negligibly worse than Weber's law, and the last negligibly better. (Here there is a hint of a minimum at 50 dB SL for H.T. and C.H. Interaural intensity and phase differences are both available for this condition.) For $\alpha = \pi/2$ rads, it is clear that every one of the four subjects shows a near miss to Weber's law. Here, most of the improvement in the Weber fraction takes place over the lower half of the range of M, again suggesting a minimum, as is clear for H.T. at 50 dB SL. Furthermore, the shape of the average Weber function for this condition nearly perfectly parallels the average monaural Weber function. Thus, on the average, a Weber function like that for homophasic discrimination very nearly obtains for antiphasic listening when there is a nonzero interaural intensity ratio alone and perhaps also in conjunction with an interaural phase difference. When there is a pure interaural phase difference, there is a related trend, and Weber's law clearly fails, yielding slopes near .90.

Further Considerations With Regard to Binaural Processes

Problems and limitations of relevant quantitative models (e.g., Colburn, 1973; Hafter, 1971; Osman, 1971; Penner, 1972; Siebert, 1968; Teich & Lachs, 1979) lead us to avoid speculation concerning mechanisms at this time, since such speculation must be limited and could be misleading. Useful theoretical work would require description of threshold dependencies on signal-masker phase angle and related interaural parameters, as well as masker intensity. Consequently, in the remainder of this paper we describe our results in terms of those parameters in relation to the relevant binaural literature.

Looking across α values for any level of masker (Tables 4, 5, and 6 and Figures 8-10), we find that the trend agrees with that reported in the literature for well-practiced subjects (Hafter & Carrier, 1970; McFadden, Jeffress, & Ermey, 1971; Robinson, Langford, & Yost, 1974; Wightman, 1971; Yost, 1972). On the average, detection improved first by 4.3-6.0 dB between 0 and $\pi/4$ rads (as some interaural phase difference is introduced), and then markedly by 6.1-11.4 dB between $\pi/4$ and $\pi/2$ rads (as only interaural phase differences appear). These antiphasic conditions typically show very large individual differences and large practice effects.[7] McFadden et al. (1971) have attempted to categorize subjects in terms of the tendency to be sensitive to interaural intensity or interaural phase (time). The pattern of individual similarities and differences in our data confirms such a categorization, particularly at the intermediate masker level. The results of our subjects for a masker of 50 dB SL are reproduced at the top of Table 7. The following observations support the argument. Both C.H. and H.T. did better than both Z.C. and T.I. with antiphasic stimuli for every value of α. For each of these pairs, differing in overall sensitivity, both members show virtually the same Weber fraction at $\alpha = \pi/4$ rads. One member of each pair, C.H. or T.I., is clearly better at discriminations of pure interaural amplitude differences (ΔR), while the other member of each pair, H.T. or Z.C., is clearly better at discriminations of pure interaural phase dif-

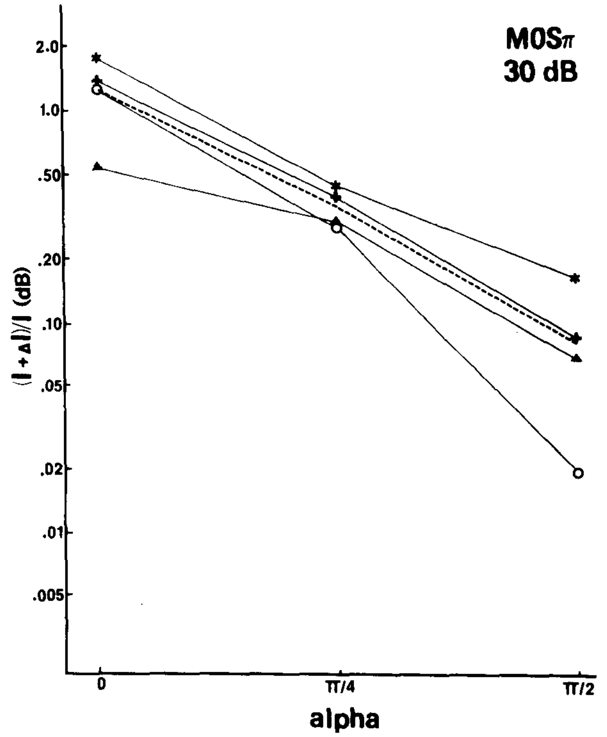

Figure 8. Values of (I + ΔI)/I in dB vs. α for the binaural condition M0Sπ with M = 30 dB SL (derived from Tables 4, 5, and 6). The symbols are results for individual subjects (+, Z.C.; ▲, C.H.; *, T.I.; ○, H.T.). The dashed line is the average over these subjects. Note again that our choice of ordinate scaling for this and the next two figures is as in Yost (1972) and differs from other studies showing similar results.

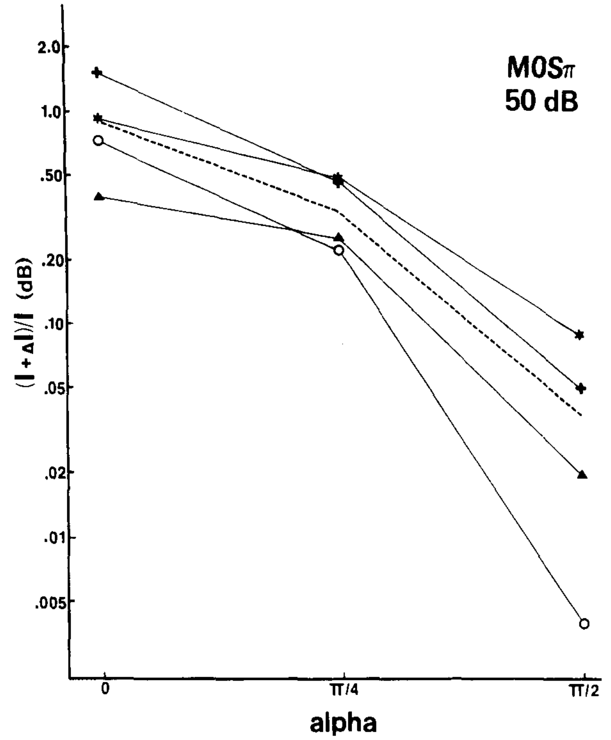

Figure 9. Values of (I + ΔI)/I in dB vs. α for the binaural condition M0Sπ with M = 50 dB SL (derived from Tables 4, 5, and 6). The symbols are results for individual subjects (+ , Z.C.; ▲, C.H.; *, T.I.; O, H.T.). The dashed line is the average over these subjects.

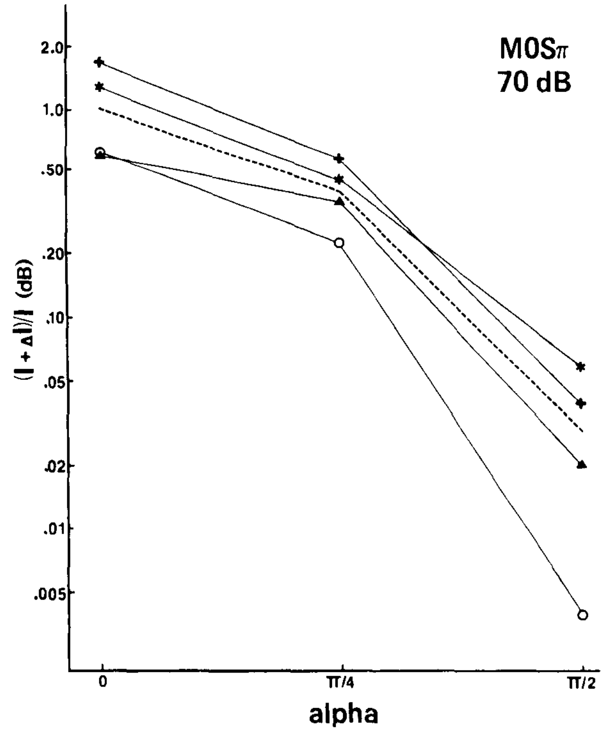

Figure 10. Values of (I + ΔI)/I in dB vs. α for the binaural condition M0Sπ with M = 70 dB SL (derived from Tables 4, 5, and 6). The symbols are results for individual subjects (+ , Z.C.; ▲, C.H.; *, T.I.; O, H.T.). The dashed line is the average over these subjects.

ferences ($\Delta\theta$). Thus, our data provide excellent support for the differential sensitivity of some subjects favoring interaural amplitude differences ($\alpha = 0$ rads) and of others favoring interaural phase differences ($\alpha = \pi/2$ rads). The values of ΔR and $\Delta\theta$ are uniquely determined by the Weber fraction and α.

In view of the large learning effects and individual differences, the most sensible thing to do is to examine and compare the data for the best individual subjects across studies. This is done, as well as possible, in Table 7, where we have collected all the results we could find in the literature comparable to our own at 250 Hz and converted all values to the form ΔI/I in dB. Unfortunately, individual subject data were available in only two other papers, Hafter and Carrier (1970) and McFadden et al. (1971). Furthermore, because of the significant differences in procedures and/or stimuli among the studies, as summarized in Table 7, comparisons of the values across the studies in the table must be made with caution. The thresholds for the Hafter and Carrier and the McFadden et al. studies were reported for d′ values larger than ours. Adjusting for the differences in d′ (by presuming the shape of the psychometric function) would appear to improve all the thresholds for both of them. However, for purposes of comparison across studies, this may not be justified, since in both cases lower thresholds are likely to have resulted from the differences in procedure. Hafter and Carrier used a "same-different" paradigm, which gives the subjects a distinct advantage over the ordinary single-interval "yes-no" task for which d′ is defined. McFadden et al. used a masker that was continuous throughout an experimental session and that should have also enhanced performance (Green, 1969). Adjustment of thresholds for these factors would tend to cancel the adjustments for d′, and, having no basis for guessing their relative magnitudes, we made neither. To make some comparisons across studies comfortably, we again use the Weber fraction results at the intermediate value of α for reference, where the lowest thresholds appear in the table within the range of −9.0 to −12.8 dB for six subjects, two from each study. Of these six, at $\alpha = \pi/2$ rads the best are S.C. and J.M. of Hafter and Carrier, W.R. of McFadden et al., and H.T. of our study. Given the qualifications discussed above, we could not hope for better agreement among individual listeners from different laboratories for the function relating ΔI/I to α. Furthermore, the agreement among the other two subjects, H.E. of McFadden et al. and our C.H., is just as satisfying. Of these two subgroups of the better subjects, the former performed consistently better than the latter at $\alpha = \pi/2$ rads, while the reverse is true at $\alpha = 0$ rads. Again, our best performers are C.H. and H.T., and their results are fairly representative of the two types of sensitivity, to ΔR and to $\Delta\theta$.

Table 7
Weber Fractions (ΔI/I, in Decibels) from Several Studies for Homophasic and Antiphasic Stimuli

								Stimulus Configuration			
Data Source	Stimuli	Signal Duration	Masker		Psychophysical Task	d′	Subject		M0Sπ (α in Radians)		
			Level	Mode				M0S0	0	$\pi/4$	$\pi/2$
Osman, Tzuo, & Tzuo (this study)											
Tables 2, 4, 5, 6	250-Hz tones	250	50*	G	2ATFC	1.00	C.H.	−12.3	−10.2	−12.3	−23.0
							H.T.	−9.7	−7.3	−12.8	−30.2
							Z.C.	−10.7	−3.7	−9.5	−19.8
							T.I.	−10.6	−6.2	−9.3	−16.6
Hafter & Carrier (1970)											
Figure 3	250-Hz tones	125	70	G	Same-Different	1.50	S.C.	−6.1	−7.9	−12.2	−29.8
							J.M.	−7.2	−8.2	−11.9	−30.3
							B.M.	−6.4	−7.9	−9.0	−21.0
McFadden, Jeffress, & Ermey (1971)											
Table 1	250-Hz "narrow-band" noises	200	68	C	Yes-No	1.68	H.E.	+.5	−9.0	*−11.5*	−24.0
							W.R.	+1.6	−7.7	*−12.8*	−30.0
							J.L.	+.4	−6.7	*−9.7*	−21.8
							S.B.	−.2	−7.8	*−10.2*	−24.0
Yost (1972)											
Figure 2	250-Hz tones	128	Average for 64, 70, 76	G	2ATFC	.95	Average for 2	−10.0	−12.1	−14.5	−25.6
Figure 3							Average for 6	−9.2	−11.0		−22.2
Wightman (1971)											
Figure 5	262-Hz "heavily filtered" tones	100	70	C	2ATFC	.95	Average for 3	−7.0	−8.3	*−11.9*	−27.5
		300					Average for 3		−10.3		−32.5
Robinson, Langford, & Yost (1974)											
Figure 5	250-Hz tones	128	70	G	2ATFC	.95	Average for 4	−8.3	−6.8	−10.7	−23.1

*Note—Signal durations are given in milliseconds; masker levels are given in decibels SPL unless otherwise denoted. C = continuous; G = gated. Italicized values for $\pi/4$ are averages for data at $\alpha = \pi/6$ and $\alpha = \pi/3$. *Decibels SL.*

Comparisons of the results of these α studies with those of "lateralization" studies designed for the measurement of interaural phase (or time) jnds (thresholds) and interaural intensity jnds are appropriate, since the same cues are involved in both. A summary of $\Delta\theta$ and ΔR jnds for all four of our subjects appears in Table 8. The most directly comparable study in print is Hershkowitz and Durlach (1969) for 500-Hz tones of 300 msec duration, a 2ATFC procedure, and a definition of jnd at d′ = .95. However, those authors intentionally avoided such comparisons because of the inconsistencies in the results of the tone-on-tone α experiments.[8] Yost (1972) discussed such comparisons and claimed excellent agreement and no dependence of interaural jnds on masker level. We believe that there is good agreement, but for the opposite reason, as supported by attention to finer details of the data. Hershkowitz and Durlach reported the results of two subjects for maskers ranging from below 20 to 75 dB SL. Examining their graphs for interaural time and amplitude on-the-midline jnds, we noticed the following. For their interaural time jnds, the data of Subject S_2 are relatively flat but do show a decline from 20 to 40 dB SL. The data of Subject S_1 show a smooth decline as a function of masker intensity up to 60 dB SL, followed by a small rise. The shape of the function for this subject is shown to be paralleled by 500-Hz results from Zwislocki and Feldman (1956), showing a minimal threshold at 50 dB SL. For 250 Hz, Zwislocki and Feldman found the minimum to occur at 70 dB SL. Our ΔI/I data for M0Sπ with $\alpha = \pi/2$ rads, converted to interaural phase differences at threshold, show a comparable result for every subject (see Table 8). The decline is consistently proportionately large from 30 to 50 dB SL and then very small, although consistent, from 50 to 70 dB SL. (Presumably, the rise should appear above 70 dB SL.) To compare the magnitudes of the jnds of the Hershkowitz and Durlach study and ours, we choose differences in interaural phase ($\Delta\theta$) rather than time (Δt). This is because, at threshold, it is $\Delta\theta$ that is independent of frequency (Yost, 1974) and, consequently, not Δt. For 50 dB SL, Hershkowitz and Durlach found an average $\Delta\theta$ at 500 Hz of 2.1 deg, agreeing with the 2-deg minimum of Zwislocki and Feldman for their longer tones at 250 Hz; our lowest comparable result is 3.6 deg, for H.T. Results of

Table 8
Trading of Interaural Phase and Intensity Differences

Masker Level	$\Delta\theta$* for $\alpha = \pi/2$ Radians	ΔR† for $\alpha = 0$ Radians	TR	For $\alpha = \pi/4$ Radians		
				$\Delta\theta$*	ΔR†	$\Delta\theta + \Delta R(TR)$*
			Subject Z.C.			
30	16.03	3.06	5.24	5.42	.82	9.72
50	11.69	3.42	3.42	6.14	.93	9.32
70	10.68	3.77	2.83	7.84	1.18	11.18
			Subject C.H.			
30	14.75	1.12	13.17	4.12	.62	12.29
50	8.15	.82	9.94	3.26	.49	8.13
70	7.39	1.20	6.16	4.86	.73	9.36
			Subject T.I.			
30	22.34	3.96	5.64	6.13	.93	11.38
50	16.76	1.98	8.64	6.37	.96	14.50
70	13.90	2.78	5.00	6.27	.95	11.02
			Subject H.T.			
30	8.22	2.75	2.99	3.85	.58	5.58
50	3.56	1.55	2.30	2.92	.44	3.93
70	3.31	1.24	2.67	2.97	.45	4.17

Note–Masker levels are given in decibels SL; TRs are given in degrees per decibel. See text for explanation.
**In degrees. †In decibels.*

other studies offering data at 250 Hz are in good agreement with this range for $\Delta\theta$ (Klumpp & Eady, 1956; Mills, 1958; Yost, 1974).

Turning our attention to interaural amplitude differences (ΔR) (see Table 8), Hershkowitz and Durlach (1969) show an average jnd of .88 dB at 50 dB SL. Their two subjects show irregular functions of masker level, but one, S_1, shows a minimum at 60 dB SL and the ΔR values are very close to ours for C.H. The other, S_2, shows a flatter function up to, and a steady decline above, 50 dB SL. (The values for S_1 and S_2 agree almost perfectly at 30, 50, and 60 dB SL.) Our jnds for H.T. show a steady decline from 30 to 70 dB SL, but H.T. was less sensitive to ΔR (by about .5 dB) than either C.H. or the subjects of Hershkowitz and Durlach. Finally, this pairing of the individual data across the two studies in terms of the form of the function is supported by an identical pairing based on sensitivity. In the respective experiments, both S_2 and H.T. were clearly best and S_1 and C.H. worst at discriminations based on interaural phase differences.

It is common practice to examine interaural jnds in terms of a trading ratio in μsec/dB. We computed a trading ratio in deg/dB, $TR = \Delta\theta/\Delta R$, using the values at $\alpha = 0$ and $\pi/2$ rads, and then used it to convert the $\Delta\theta$ and ΔR pairs at $\alpha = \pi/4$ rads to an "equivalent $\Delta\theta$." The computations (Table 8) show agreement within 3 deg for 10 of the 12 comparisons of the magnitudes of such equivalent phase shifts across α for our subjects. This suggests that discrimination may be based on some simple combination of $\Delta\theta$ and ΔR cues when they are in consonance (Hafter & Carrier, 1970). The size of our trading ratio ranges from 2.30 to 13.17 deg/dB, or approximately 25 to 145 μsec/dB. Its dependence on intensity level for individual subjects and comparisons with results of other studies naturally reflect the matters already discussed. (Hershkowitz and Durlach, 1969, provide further discussion of the time-intensity trading ratio.)

SUMMARY

We have examined Weber functions for gated 250-Hz tones for monaural and several binaural stimulus conditions for maskers from 30 to 70 dB SL. The various cues for discrimination of signal-plus-masker from masker alone are functions of intensity increments at one or both ears, an intensity increment at one ear coupled with a decrement at the other, or the introduction of a phase difference between the ears. The decline of the Weber fraction with increasing masker level was nicely confirmed for monaural discrimination over the entire 40-dB range, and a similar rate of decline was found for various binaural stimuli over the lower half of that range. This may be a coincidence, but it at least suggests that some common underlying statistics mediate the various results. The precise nature of the various departures from Weber's law for binaural stimuli, however small, could be of theoretical significance, as was demonstrated by McGill and Goldberg for the "near miss."

To provide a fuller analysis of our results with a view towards future theoretical work, we also examined our results for antiphasic stimuli as a function of the phase angle of addition of signal to masker.

The results support other research and the categorization of subjects with respect to differential sensitivities to interaural phase and interaural amplitude shifts.

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NOTES

1. Tones were generated by a single oscillator and then split into electrically isolated channels for signal and masker. Signal-masker phase shifts were produced as time delays using a Reticon Analog Delay Line (SAD-1024). The signal was gated by a Grason-Stadler electronic switch (829E) to overlap one or the other of the two observation intervals on each trial. Signal and masker were split again into two isolated channels for left and right earphones, and one resulting signal was inverted when required. Signal and masker were then summed for each earphone using resistive mixers. Both sums were then gated by a two-channel Grason-Stadler electronic switch (829E) for the duration of each observation interval, and then passed to the two TDH-39 earphones via impedance matching transformers. (For each TDH-39 earphone, a .1-V rms input at 250 Hz yields an output of 107 dB SPL.) Attenuation and filtering were employed at various points throughout the network. Note that time shifts were accomplished prior to gating so that left- and right-ear stimuli were properly synchronized. Also note that the monaural stimuli were always presented to the right ear, which was the most sensitive of the two ears for all listeners. All stimulus parameters were carefully and regularly calibrated by measurements made at the input to the earphones using a dual-beam oscilloscope, a Ballantine True RMS voltmeter (320A), and a Krohn-Hite phase meter (6200A). We believe that neither training nor equipment artifacts could explain the results we obtained.

2. There was considerable variation in the slope values (k) for the best fitted psychometric functions over subjects and conditions. We did not find any patterns that suggested that those slopes depend on any of our experimental parameters. For the 75 values of k for our discrimination data, the mean was .97 and the standard deviation was .35.

3. To get the Weber fraction averages in these tables, we first computed geometric means of voltages and then converted those results to decibels. Rounding error would thus account for any apparent inaccuracies. The average slopes are the best fitted slopes for the average thresholds.

4. In Yost (1974), there is a discrepancy between the values shown in his graphs and his discussion of them. He comments that his homophasic Weber fractions, $(I+\Delta I)/I$, stayed at .7 dB over his 12-dB range of I, in agreement with classical monaural results. However, his ordinates are scaled in log decibels, and the homophasic fractions are about .65 of a log unit above (or 4.4 times greater than) .1, which puts them at a value of .44 dB. This agrees well with our values in the region around 50 dB SL.

5. Although our subjects all reported that the 70-dB SL homophasic masker was very loud, they did not feel that it was sufficiently annoying to interfere with their performance in the 2ATFC task.

6. We could convert our $M0S\pi$ data using a sort of Weber fraction similar to $\Delta I/I$, $\Delta R_L/R_L(\mathrm{dB}) = 10\log(R_R^2 - R_L^2)/R_L^2$. The idea suggests that the subject compares I with $(I+\Delta I)$ across observation intervals when no interaural differences exist and across ears when they do. (The numbers would be larger in this form, since both increments and decrements to M are involved.) In terms

of the shape of the Weber function, however, the results are just as well characterized by $\Delta I/I$.

7. For example, Hafter and Carrier (1970) displayed "learning data" for their best subject (J.M.) at 250 Hz for M0Sπ with $\alpha = \pi/2$ rads. Six determinations of performance over a period of 2 months show a 10- to 15-dB improvement in threshold. Our own subjects support the finding. The data (Tables 4 and 6) for Z.C., C.H., and T.I. at $\alpha = 0$ rads and Z.C. and C.H. at $\alpha = \pi/2$ rads are the results of a complete replication of the experiment for those conditions. For $\alpha = 0$ rads, improvement was negligible for C.H. and T.I. but significant for Z.C., the largest being 6.8 dB. For $\alpha = \pi/2$ rads, every threshold improved for both Z.C. and C.H., the range being from 4.6 to 14.0 dB.

8. For the α studies, interaural intensity differences are introduced as asymmetrical shifts in level (dB) at each ear for $\alpha = 0$ rads, ΔR and $\Delta\theta$ are combined in consonance (tending to shift the subjective image in the same direction) for $0 < \alpha < \pi/2$ rads, and interaural time shifts are accompanied by intensity increments at both ears for $\alpha = \pi/2$ rads. These intensity increments are very small at threshold but might be significant at higher signal levels in the course of testing. In the context of the experiment, therefore, subjects may be confused with regard to which cue is most relevant, leading to the large individual differences and improvement with practice. For the study of Hershkowitz and Durlach, interaural intensity differences were set to be symmetrical and interaural time shifts were not accompanied by any changes in intensity.

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