SUBJECTIVE LATERAL POSITION AND INTERAURAL DISCRIMINATION

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ABSTRACT

This paper compares interaural discrimination performance at 500 Hz to predictions of a model that generates estimates of subjective lateral position. The model assumes that interaural timing information is obtained from comparisons of auditory-nerve firing times, and that this information is weighted by a function that depends on the interaural intensity difference of the stimulus. Predictions for interaural discrimination experiments are obtained by assuming that performance is based on changes in lateral position of a single dominant spatial image and its variance, and that performance is limited by the intrinsic variability of the auditory-nerve response to the stimuli. The predictions (at least qualitatively) describe most of the observed experimental data, including a number of results that have not been addressed by any previous theory. Nevertheless, observed performance is significantly better than the corresponding predictions for three types of experiments in which the utility of the position cue has been eliminated by experimental design. We believe that our results indicate that changes in lateral position are the primary cue in most interaural discrimination experiments, but that secondary stimulus attributes can be useful when performance based on position alone would be poor.

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INTRODUCTION

Subjective lateral position is a prominent cue in many psychoacoustical experiments in which interaural parameters are varied. For example, Klumpp and Eady (1956), Hershkowitz and Durlach (1969a), Yost (1974), and Domnitz and Colburn (1977) have all specifically cited the use of lateral position cues in their experiments measuring just-noticable differences (jnds) of interaural time or intensity. Theoretical studies comparing various interaural discrimination results to changes in subjective position include recent work by Hafter and Carrier (1970), Hafter (1971), Yost (1970), and Domnitz and Colburn (1977).

In this paper, we attempt to assess how well performance in a variety of interaural discrimination experiments using 500-Hz binaural stimuli may be "accounted for" by optimal use of changes in the lateral position of a single auditory image. This assessment is obtained by comparing the experimental data to predictions from the model for subjective lateral position described in our previous paper (Stern and Colburn, 1978). This model, referred to as the position-variable model, generates estimates of subjective lateral position from operations on auditory-nerve activity. The position estimates are random variables with distributions derived from the inherently random nature of the auditory-nerve activity.

Our predictions of performance in interaural discrimination experiments are based on calculations of the performance index d' for the relevant experiment. We assume that this quantity d' depends only on the mean and standard deviation of a decision variable called $\hat{P}$, the predicted subjective lateral position for a given acoustical stimulus. The specific formulae for calculating $E[\hat{P}]$ and σ_P, the mean and standard deviation of $\hat{P}$, are given in Stern and Colburn (1978).

Except for the specific functions relating $E[\hat{P}]$ and σ_P to the 500-Hz stimuli, this model derives predictions in the same way as other theories collectively referred to as "lateralization models" (Hafter and Carrier, 1970; Yost, 1970; Domnitz and Colburn, 1977). The difference between our model and the others are in the functions $E[\hat{P}]$ and σ_P, and how they are generated. Except for the work of Domnitz and Colburn (1977), the previous lateralization models have assumed a fixed σ_P and a function $E[\hat{P}]$ that is a linear combination of the interaural time and intensity differences of the stimulus. According to available data on subjective lateral position (Sayers, 1964; Domnitz and Colburn, 1977; Yost, 1981), this applies for 500-Hz tones only to stimuli with interaural intensity differences of approximately 0 dB and time delays of approximately 0 or ±1000 μs. Predictions of all models will be similar for stimuli with these parameter values. The model developed by Domnitz and Colburn (1977) characterizes $E[\hat{P}]$ empirically and uses a value of σ_P that is fitted to data from interaural amplitude jnd experiments; their model can predict the results of interaural time jnd experiments. The distinguishing characteristic of our model relative to previous work is that it is generative and applies to all values of interaural time and intensity differences. This enables us to consider a broader set of experimental data than was examined in previous theoretical studies of interaural discrimination.

Because we are most interested in general issues concerning the single lateral position cue as a useful predictor of interaural discrimination performance, we discuss the success or failure of the position-variable model in terms of the trends of its laterality predictions, rather than the specific bases within the model that give rise to these predictions. These bases are considered in detail in Stern and Colburn (1978). We also attempt to distinguish between inaccurate predictions that we believe are the result of specific assumptions of the position-variable model (and hence could possibly be ameliorated by a reformulation of the model) from those failures that appear to be characteristic of all models that predict discrimination performance from changes in the position of a single image.

In Sec. I we briefly review some of the major features of the position-variable model and we describe how it is applied to the interaural discrimination experiments. In Sec. II we compare the predictions of the model to measured performance in these experiments. In Sec. III we discuss in more detail those experiments in which the data are not predicted using only the position-related variable.

I. THE POSITION-VARIABLE MODEL AND ITS APPLICATION TO INTERAURAL DISCRIMINATION EXPERIMENTS

The position-variable model was developed to relate the results of a more diverse set of data regarding the lateralization, discrimination, and detection of binaural 500-Hz tones than had previously been considered within the framework of any single theory. We briefly review some of the salient features of the model and its predictions for lateralization, and discuss how these predictions are applied to interaural discrimination experiments.

Any model that describes auditory lateralization must specify how information pertaining to the interaural time delay (ITD) and interaural intensity difference (IID) of the stimulus are extracted, and how this information is combined to form a fused spatial image. In the position-variable model, as described in detail in Stern (1976) and Stern and Colburn (1978), information pertaining to the ITD is contained within a timing function, the IID information is contained within an intensity function, and the position variable $\hat{P}$ is generated by computing the centroid (or center of mass) of a function called the position function, which is equal to the product of the timing and intensity functions. The timing function is related to the interaural crosscorrelation of the stimuli, and is generated from the outputs of coincidence counters of auditory-nerve activity, with specified characteristic interaural delay. Specifically, the timing function is defined to be the total number of counts of a network of such units as a function of their interaural delay. This function may be regarded as a quantification of earlier theories suggesting crosscorreltion mechanisms (Jeffress, 1948; Sayers and Cherry, 1957; Licklider, 1959). The intensity function is assumed to be a Gaussian-shaped pulse of constant width, with a location that depends on the IID of the stimulus.[1] The location of the intensity function is a saturating nonlinear function of IID that has been fitted to most closely describe lateralization-matching data, and is shown in Fig. 4 of Stern and Colburn (1978).

In applying the model to interaural discrimination experiments we first compute $E[\hat{P}]$ and σ_P for each of the two stimuli to be discriminated. The performance index d′ is calculated for these stimuli by assuming that the random variable $\hat{P}$ is Gaussian and that the decision device can make use of differences in both the means and variances of the $\hat{P}$s for the two stimuli to be discriminated. This procedure is iterated until we determine the pairs of stimuli producing the appropriate criterion value of d′ for each experiment considered.[2]

We generate separate predictions for individual subjects for experiments in which the simpler position description of the lateralization model is also valid. This is accomplished by assuming that the location of the intensity-weighing pulse is linearly proportional to the IID, and choosing a proportionality constant to fit the observed time-intensity trading ratio. (This assumption is valid for IIDs up to about 7 dB in magnitude as seen in Stern and Colburn, 1978.) We indicate the data points to which this additional free parameter is fitted when appropriate. We do not provide predictions for individual subjects in experiments with stimuli that include larger ITDs and IIDs because the parameter-fitting procedures for these experiments are considerably more complex and tedious (cf. Stern and Colburn, 1978, footnote 6).

The model is illustrated for a 500-Hz tone with an ITD of 500 μs (right leading) in

Fig. 1. The expected value of the timing function is shown in Fig 1a; the intensity function for two IIDs in Figs 1b and 1d (the more intense stimulus is to the right in Fig. 1b and to the left in Fig. 1d). The position functions for these cases are shown in Figs. 1c and 1d, respectively. The centroid of the position function (i.e., the predicted mean lateral position) is indicated by the heavy vertical bar in each example. As noted above, we refer to the predicted estimate of subjective lateral position by the random variable $\hat{P}$, whose variability is a consequence of the stochastic nature of the auditory-nerve activity.[3]

In Fig. 2 we plot for a 500-Hz tone $E[\hat{P}]$ and σ_P, the mean and standard deviation of $\hat{P}$, as a function of ITD, varying IID as a parameter.[4] Our notational conventions are such that small positive ITDs or IIDs would tend to cause a sound to be lateralized toward the right side of the head. We refer to plots of $E[\hat{P}]$ as in Fig. 2a as "position curves," and we define the "cue-reversal points" of these curves to be the ITDs for which the curves exhibit zero slope. The phrase "cue reversal point" refers to the fact that a small increase in the ITD of a tone causes its subjective position to move toward the right for ITDs between the two cue-reversal points surrounding 0 μs, and to the left otherwise.

The attributes of the position curves (Fig. 2a) that are central to our predictions are: (a) the approximate linearity of the curves for IIDs of small magnitude and ITDs of approximately 0 or ±1000 us, (b) the existence of cue-reversal points and their dependence on the IID of the stimulus, and (c) the overall dependence of the slopes and separations of the position curves on the ITD and IID of the stimulus.[5] These attributes are consistent with the results of subjective laterality measurements by Sayers, (1964) and Domnitz and Colburn (1977), as discussed in Stern and Colburn (1978).[6]

The attributes of σ_P, the predicted standard deviation of $\hat{P}$ (Fig. 1b) that are important for the discrimination data are (a) the overall increase in σ_P as the ITD or IID of the stimulus increases in magnitude, and (b) the mild tendency for σ_P to be greater when the ITD and IID are of opposing sign. These predictions are at least qualitatively consistent with a similar variable called the "position parameter" derived by Domnitz (1975) to relate interaural time and amplitude discrimination results to results from a lateralization-matching experiment using 500-Hz tones. More recently, Smith (1979) derived a measure of position variance from performance in laterality-comparison experiments, incorporating an explicit functional relationship between IID and subjective lateral position. It is difficult to critically compare Smith's data with the present predictions because his data are reported in units describing the perceived location of a subjective image inside the subject's head, while our predictions are computed in terms of units representing the physical IID of the stimulus. The function relating stimulus IID and subjective position is highly nonlinear, and the rate of change of position with respect to IID decreases rapidly as the magnitude of the IID increases. At larger IIDs the fit of the predictions to the data becomes critically dependent on the exact shape of this function.

II. COMPARISON OF PREDICTIONS AND DATA

We compare the predictions of the position-variable model first to pure interaural time and amplitude jnds, and subsequently to discrimination experiments measuring sensitivity to simultaneous changes of interaural time and intensity. For all these experiments we will discuss comparisons of predictions and data in terms of the ratio of the jnds obtained at a given ITD and IID and that same jnd obtained with zero ITD and IID. We also include in our comparisons detection experiments with coherent targets and maskers, and in these experiments thresholds are described in dB relative to the $N0S\pi$ threshold.[7]

A. INTERAURAL TIME JNDS

Predictions for normalized interaural time jnds as a function of the reference ITD are compared to experimental results using equal-amplitude stimuli (Hershkowitz and Durlach, 1969a; Domnitz, 1973; Yost, 1974; Domnitz and Colburn, 1977, and Moss, 1979) in Fig. 3, and to results for tones with 20-dB amplitude-shifted stimuli (Domnitz and Colburn, 1977) in Fig. 4. The open data points and broken theoretical curves in Figs. 3 and 4 indicate observed and predicted stimulus conditions that give rise to a reversal in the direction of the lateralization cue. Data from individual subjects are plotted separately in Fig. 4 because of the great amount of observed intersubject variability.[8]

Considering first the properties of the data that are predicted by the model, we note that the magnitude of the time jnd measured with zero ITD is at least 2 to 5 times greater for tones presented with the 20-dB interaural intensity difference than for the equal-amplitude tones. This trend is seen in the predictions because σ_P increases with increases of the IID (Fig. 2b). Reversals in direction of the lateralization cue are observed for time delays near ±1000 μs for the equal-amplitude tones, and between approximately -500 and ±1000 μs and between +700 and ±1000 μs for the amplitude-shifted stimuli. (Similar reversals have been noted by Hershkowitz and Durlach, 1969a; Domnitz, 1973; and Yost, 1974.) The predicted cue reversals are a consequence of the quasi-sinusoidal shape of the position curves in Fig. 2b, and specifically the nonmonotonic dependence of $E[\hat{P}]$ on ITD. The time jnd for the 20-dB amplitude-shifted stimuli is a strongly nonmonotonic function of reference ITD, and is asymmetric with respect to time delay. (For example, more sensitive discrimination performance generally is observed when the louder signal is also leading in time for values of reference ITD up to about 500 μs in magnitude.)

The most significant discrepancy between the predictions and data of Figs. 3 and 4 is that performance much worse than observed (large jnds) is predicted for some time delays in each of the theoretical curves. This trend is actually observed only in the amplitude-shifted data of Subject MT. For each IID, the ITDs for which large jnds are predicted are approximately the cue-reversal points on the corresponding position curves of Fig. 2a, so the predictions of poor performance in this region arise from the relatively small changes in $E[\hat{P}]$ as the ITD is incremented or decremented.

A more critical analysis of the available time-jnd results in terms of the model is difficult because cue-reversal points for a given value of IID can vary by as much as 400 μs from subject to subject (Domnitz and Colburn, 1977), and there has been relatively little discrimination data collected at time delays near cue-reversal points. Moss (1979) recently performed the most comprehensive set of such measurements. He found that while time-jnd performance is much worse for values of ITD between 500 and 1000 μs, subjects frequently make use of cues other than subjective lateral position in performing these more difficult tasks. He noted that specific cues used could vary greatly, even from trial to trial of a given experiment, and this lability of the perceptual cue probably contributes to the high variability and poor performance seen in the data. We discuss this problem in more detail below.

B. INTERAURAL AMPLITUDE JNDS

Predictions for relative interaural amplitude jnds as a function of the reference ITD are compared to data by Rowland and Tobias (1967), Hershkowitz and Durlach (1969), and Domnitz and Colburn (1977) in Fig. 5. The filled symbols and solid curves indicate data and predictions obtained with a reference IID of 0 dB, while the open symbols and broken curves refer to stimuli presented with an IID of 20 dB. The predictions and data are plotted as ratios to the amplitude jnd obtained with a reference ITD and IID of zero in the same fashion as the time jnd results in Figs. 3 and 4.

The data and predictions of Fig. 5 are in fair quantitative agreement, with the greatest failure of the model being its underestimation of amplitude jnds for amplitude-shifted stimuli with ITDs of small magnitude. The most obvious difference between the form of the time and amplitude discrimination data in Figs. 3-5 is that the amplitude jnds vary only over a range of up to 5:1 as ITD and IID are varied, compared to the range of greater than 16:1 seen in the time-jnd data. Also, the cue reversals that had been observed for some stimulus conditions in the time-jnd experiments are not perceived under any conditions when measuring amplitude jnds. Both of these attributes of the data are predicted by the position-variable model because $E[\hat{P}]$ is a monotonic function of IID for all ITDs and IIDs. (In contrast, $E[\hat{P}]$ is a monmonotonic function of ITD.[9]) While the amplitude-shifted data in Fig. 5 are basically symmetric with respect to ITD, the predicted amplitude jnds for reinforcing ITD and IID are slightly larger than the jnds predicted for cancelling combinations.[10] This asymmetry is a consequence of an interaction between two conflicting trends in $E[\hat{P}]$ and σ_P. In particular, it is seen in Fig. 2 that the change of $E[\hat{P}]$ with a small change of IID is greater when the ITDs and IIDs cancel compared to when they reinforce one another. On the other hand, σ_P also tends to be greater when the ITD and IID are cancelling. Since the jnd is inversely proportional to the change in $E[\hat{P}]$ divided by σ_P, these two trends have opposite effects on the amplitude-jnd predictions.

Kearney (1979) and Leshowitz et al. (1974) have demonstrated that randomization of the overall loudness of stimuli in amplitude jnd experiments tends to cause the observed discrimination performance to become worse as the reference IID is increased in magnitude. These results suggest that subjects in most previous studies (e.g. Domnitz and Colburn) may have been making use of monaural information in performing the discrimination task. It is probable then, that the 20-dB amplitude-shifted data would have been more closely described by the predictions of Fig. 5 (at least for values of ITD of small magnitude) if the experiment had been performed with randomized overall amplitudes.

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The remaining studies to which the model is compared are concerned with measurements of sensitivity to simultaneous changes of interaural time and intensity. These experiments all use stimuli with ITDs and IIDs within a small region of either 0 us and 0 dB or 1000 us and 0 dB. In either case, $E[\hat{P}]$ is found to be a linear function of ITD and IID, and σ_P is approximately constant. This description of position and its standard deviation is also used in comparing Hafter's lateralization model (Hafter and Carrier, 1970, Yost, 1970) to discrimination data, so that all available models will give the same predictions for these experiments.

C. COHERENT-MASKING STUDIES

Probably the largest body of measurements of sensitivity to simultaneous changes of ITD and IID has been obtained using a "coherent-masking" paradigm. This includes the numerous binaural tone-on-tone masking experiments as well as experiments using targets and maskers derived from a common narrowband noise source. These studies are all similar in structure to measurements in which subjects are required to detect the presence of a tone in noise, except that target and masker are both pure tones or deterministically-related narrowband noises of the same frequency, so that the ITDs and IIDs of the total stimuli are deterministic. As a result, the experimenter is able to control the phase of the target relative to that of the masker, as well as the ITD and IID of the target and masker. In the $NOS\pi$-type experiment condition the masker is interaurally in phase and the target is out of phase. In the $N\pi S0$ condition the masker is out of phase and the target is in phase. In either case the interaural differences of the combined target and masker depend on the target-to-masker ratio and target-to-masker phase angle.[11]

1. Tone-on-Tone Masking

Many investigators have described the results of various tone-on-tone masking experiments (cf. Jeffress, Blodgett, Sandel, and Wood, 1956; Wightman, 1969; Hafter and Carrier, 1970; Yost, 1970; and Yost, Nielson, Tanis, and Bergert, 1974). The results of all of these studies except for Wightman's appear to be mutually consistent (within the limits of common intersubject variability), so we will restrict our detailed attention to only a small representative sample. For example, Hafter and Carrier (1970), Yost (1972), and others have compared the predictions of the lateralization model to the dependence of tone-on-tone masking thresholds in the $NOS\pi$ condition as a function of the relative target-to-masker phase.

Since our predictions are identical to those of the lateralization model for these experiments we do not repeat these comparisons in detail here. The predictions generally fit the data fairly well for target-to-masker phase angles between 0 degrees and 90 degrees, the angles for which the combined target and masker exhibits reinforcing combinations of ITD and IID. On the other hand, for target-to-masker phase angles of 135 degrees, when the combined target-masker ITD and IID cancel one another, measured thresholds are as much as 13 dB lower than the corresponding predictions. (We believe that the agreement between these data and the predictions would be even worse if measurements were taken at target-to-masker phase angles of approximately 110-120 degrees.) The tone-on-tone masking data for these phase angles are therefore inconsistent with the predictions of both our position-variable model and lateralization models.

The only coherent-masking experiments in which stimuli were presented using conditions other than $N0S\pi$ are those of Yost, Nielson, Tanis, and Bergert (1974), who compared tone-on-tone masking thresholds in the $N0S\pi$ and $N\pi S0$ conditions for three target-to-masker phase angles between 0 degrees and 90 degrees. We obtained individual predictions for the three subjects in this experiment by choosing for each an intensity-weighting function to fit the $N0S\pi$ 90-degree data points.[12] (The overall predicted sensitivity for each subject is also a free parameter, as in the previous calculations.) Predicted and observed tone-on-tone detection thresholds using the configurations $N0S\pi$ (solid curves and circular symbols) and $N\pi S0$ (broken curves and square symbols) are plotted in Fig. 6 as a function of target-to-masker phase. The model correctly describes three major trends of the remaining data without further assumptions although most of the observed $N\pi S0$ thresholds are greater than the corresponding predictions. We note first that the $N0S\pi$ and $N\pi S0$ thresholds at 0 degrees target-to-masker phase are approximately equal for both the predictions and data. This is equivalent to noting that for equal-amplitude stimuli, interaural amplitude jnds with ITDs of 0 and 1000 μs are approximately equal, which was observed in the predictions and data of Fig. 5. Second, the $N0S\pi$ thresholds are lower than the $N\pi S0$ thresholds at 90 degrees target-to-masker phase. This reflects the fact that observed interaural time jnds with equal-amplitude stimuli are lower when the IID equals 0 μs than when it equals 1000 μs, which is seen in the predictions and data of Fig. 3. Third, the difference between the $N0S\pi$ and $N\pi S0$ thresholds in Fig. 6 tends to increase as the target-to-masker phase angle is increased from 0 to 90 degrees.

2. Narrowband Noise-on-Noise Masking

Jeffress and McFadden (1971), McFadden, Jeffress, and Ermey (1971), and McFadden, Jeffress, and Lakey (1972) described the results of coherent-masking experiments using narrowband-noise targets and maskers at various frequencies. We compare the predictions of the position-variable model to the results of the study by Jeffress and McFadden (1971), which explored the relative effectiveness of interaural time and intensity differences in detection and lateralization performance at 500-Hz. Using 50-

Hz bandwidth targets and maskers, Jeffress and McFadden measured $NOS\pi$ detection thresholds, $NOS\pi$ "lateralization thresholds," and the percentage of consistent lateralizations at a fixed target-to-masker ratio, all as a function of target-to-masker phase. In the detection experiment, subjects indicated whether or not the target stimulus was perceived to be present, as in tone-on-tone masking. In the lateralization-threshold experiment the target was presented on every trial, but the acoustical inputs to the two ears were randomly interchanged, and subjects indicated the side of the head toward which the target-masker complex was perceived. The stimuli for the third experiment, called an "α-sweep experiment" (where α represents the target-to-masker phase angle), were the same as in the lateralization-threshold measurements, and the percentage of consistent lateralizations was measured as a function of target-to-masker phase for a fixed target-to-masker ratio.

We obtained predicted detection and lateralization thresholds for the narrowband-noise stimuli as if they were pure tones, and plot these predictions and data as a function of target-to-masker phase in Fig. 7. Predicted and observed consistent lateralization percentages in the α-sweep experiment are plotted as a function of target-to-masker ratio in Fig. 8. For each of the two subjects in Figs. 7 and 8, the lateralization-threshold predictions at 0 and 90 degrees are fit to the data as for the Yost et al. (1974) detection experiment above; predictions for detection thresholds (square symbols in Fig. 7) and the α-sweep percentages (Fig. 8) were obtained without further assumptions.

We find very good general agreement between the predictions of the position-variable model and the data in the lateralization-threshold experiment (circular symbols in Fig. 7) and the α-sweep experiments (Fig. 8). Although the two subjects HE and WR exhibit markedly different abilities in making use of time and intensity cues, their performance for all target-masker phases in both the lateralization-threshold and α-sweep experiments can be predicted fairly accurately by the model, with an appropriate assumed trading ratio for each subject. (The lateralization model would describe these data equally well.) We note that it is not necessary to assume the existence of a secondary "time image" (as had Jeffress and McFadden) in discussing the intersubjects variability in the lateralization-threshold and α-sweep experiments.

On the other hand, the agreement of the predictions of the position-variable model to the detection-threshold data (square symbols in Fig. 7) is poor, particularly for target-to-masker phase angles between 90 and 150 degrees. We have found that choosing the location of the intensity-weighting function to fit the detection data rather than the lateralization-threshold data at 0 and 90 degrees target-to-masker phase does not significantly improve the overall fit of the predictions to the detection data. As in the time-jnd experiments and the tone-on-tone masking experiments, the measured performance is considerably better than what is predicted by the model, indicating that subjects in these experiments could be making use of other attributes of the stimuli besides subjective position. These data will be reexamined in Sec. III below.

D. TIME-INTENSITY TRADABILITY EXPERIMENTS

Discrimination results obtained by Hafter and Carrier (1972), Gilliom and Sorkin (1972), Smith (1976), and Ruotolo, Stern, and Colburn (1979) appear to imply that a single parameter such as lateral position is an insufficient characterization of the perception of a dichotic tone. For example, Hafter and Carrier found that a centered dichotic tone with the signal to the louder ear lagging in time or phase could be distinguished reliably from a centered diotic tone even when the interaural differences are as small as 30 μs or 1 dB. These results are said to indicate a less-than-complete "trading" of time and intensity information, and have been ascribed (Hafter and Carrier, 1972) to the existence of multiple images previously described by Whitworth and Jeffresss (1961) and Hafter and Jeffress (1968). We have applied the position-variable model to these experiments and found that it predicts discrimination performance near chance, even though there may be slight differences in σ_P for the two stimuli to be discriminated. This is not surprising because the position-variable model assumes that interaural discrimination performance is based on the perception of a single spatial image. Hence, it is by construction unable to predict the results of experiments in which subjects base their judgments on the perception of secondary images. We discuss this issue in greater detail below.

III. DISCUSSION

In comparing the predictions of the position-variable model to the results of interaural discrimination experiments we have found:

- The agreement between the predictions of the model and the dependence of pure interaural time and amplitude jnds on ITD and IID varies from subject to subject. The model correctly predicts the cue-reversal phenomenon and the asymmetry with respect to time delay of the amplitude-shifted time jnds, which are seen in the data of all subjects. The model also predicts extremely large values of time jnds that are observed at certain time delays only for some subjects. The model correctly predicts a lack of cue reversal for amplitude jnds, a weaker dependence of amplitude jnds (compared to time jnds) on ITD, and an overall increase of both time and amplitude jnds with increasing IID.

- The model describes many of the trends of $NOS\pi$ and $N\pi SO$ coherently-masked detection data for target-to-masker phase angles between 0 and 90 degrees, and all of the results of Jeffress and McFadden's (1971) lateralization and α-sweep experiments.

- The model cannot successfully describe the observed absence of extremely large time jnds for some subjects, and the good observed performance in coherent-masking detection experiments for target-to-masker phase angles between 90 and 150 degrees. The predictions of the model also do not agree with the good performance observed when discriminating between two binaural tones with apparently-identical subjective positions. When experimental results are in obvious conflict with the theoretical predictions, the observed performance is better than predicted. We note that all of these results are problematical not only for the position-variable model considered in this paper, but for any other model that attempts to relate discrimination performance to subjective lateralization as well.

In general, the comparisons of predictions and data support the hypothesis that performance in most interaural discrimination experiments is based on changes of lateral position, but additional information may be used in experiments for which performance based on position alone would be poor. For example, it appears that the time-jnd performance of subjects such as MT (in Fig. 3) is based on lateral position of a single image while the observed performance of other subjects (such as RD) is significantly better for some time delays near cue-reversal points. We postulate that the intersubject variability in the time-jnd data and the good performance of some subjects relative to the predictions of the position variable model may indicate that these subjects have learned to use an additional perceptual cue when changes of subjective lateral position of the stimuli are small. This hypothesis is supported by the subjective reports of subjects in Moss' (1979) experiments cited above. The notion of an additional cue was also previously suggested by Jeffress and McFadden (1971) in a discussion of their detection experiments with coherent maskers.

A number of investigators have suggested that observed performance in experiments directly measuring time-intensity tradability (such as Hafter and Carrier, 1972; Gilliam and Sorkin, 1972; Smith, 1976; Ruotolo, Stern, and Colburn, 1977) indicates that subjects are able to make use of secondary subjective images of the stimuli. However, there is a lack of agreement concerning the exact nature of the postulated secondary image. Specifically, Whitworth and Jeffress (1961) and Hafter and Jeffress (1968) have described a "time image" that is almost completely independent of the IID of the stimulus. A different type of secondary image, described by some subjects in the experiment of Ruotolo, et al. (1979), appears at the ear receiving the signal that is of greater intensity but lagging in time. A third type of multiple image can be perceived in either ear when certain subjects are presented with an equal-intensity pure tone of ITD equal to half the stimulus period, as reported by Sayers (1964), Yost (1981) and others.

The actual additional subjective cue (besides lateral position) could be a secondary perceptual image, or a difference in image diffuseness, shape, or some other quality between the two stimuli to be discriminated. It is not at all obvious that the same type of additional information is used for each of the three classes of results that are not predicted by the position-variable model. These subtleties in the subjective image of binaural sounds may be of concern to those who measure binaural perception in a clinical setting, in that untrained subjects may not respond according to these secondary stimulus attributes of the stimuli when changes of lateral position are not available as a cue.

Although it is relatively easy to modify the position-variable model to predict the types of secondary images that have been described to date, we are not attempting to rigorously develop decision variables to describe any of these images at present.[13] We have found the subjective percepts to be extremely complex even for a pure tone, and we have had difficulty separating this complexity into simple variables. It appears that the system is relatively "plastic" and that many different aspects of the stimulus can be isolated by a careful, trained observer and used as a decision variable.

In general, a model based on lateral position (and the position-variable model in particular) can account for many of the salient features of the data. There are other perceptual attributes that are used in some experiments, but these other attributes appear to affect discrimination performance when the mean lateral position cue is eliminated by careful experimental design. Almost all of the other results in interaural discrimination can be accounted for by a model based on changes of the lateral position of a single image and its variability.

IV. SUMMARY AND CONCLUSIONS

In this paper we have compared the performance of the position-variable model of binaural interaction to the results of interaural discrimination experiments using 500-Hz stimuli. Discrimination predictions were obtained assuming that judgments are made on the basis of the subjective lateral position of the stimuli, and that performance is limited by the variability of the auditory-nerve response to a given stimulus. We have also attempted to point out the attributes of the mean and standard deviation of the model's position variable $\hat{P}$ that contribute to the predictions for discrimination experiments.

The predictions of the model are in at least qualitative agreement with most of the discrimination data to which it is compared. In three types of experiments the observed performance is significantly better than the performance predicted by the model. The model provides generally good predictions for experiments in which subjects report using position as the major cue, while in many of the experimental results that differ from the predictions, great intersubject variabiliity is noted, and the task is characterized by subjects as difficult to perform. We believe that lateral position is used as the subjective cue in all experiments considered, and that some additional cues are used for those experiments in which performance on the basis of lateral position alone would be very poor. To the extent that our model accurately characterizes lateral position and its variability, these discrepancies between discrimination data and predictions would also be seen in the performance of any model in which judgements are assumed to be based solely on the lateral position of a single perceptual image.

We conclude that the position-variable model is a reasonable first-order characterization of most interaural discrimination phenomena at 500 Hz. It is more general than most other models of binaural interaction, and has the additional advantage of an explicit source of internal noise that can be related to peripheral auditory physiology.

ACKNOWLEDGEMENTS

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FOOTNOTES

1. The Gaussian shape was chosen somewhat arbitrarily for the intensity weighting function. We found in preliminary calculations that the particular shape of the weighing function did not greatly affect the form of the model's prediction.

2. For most of the experiments discussed in this paper, the change in the variance of $\hat{P}$ from interval to interval is small compared to the change in the expected value of $\hat{P}$. For these experiments a just-noticeable difference (jnd) is predicted to be that stimulus increment which produces a shift in expected value of $\hat{P}$ equal to its standard deviation.

3. We note that the use of a modified crosscorrelation function to represent interaural timing information, the multiplication of this function by a second pulse-shaped function related to interaural intensity difference, and the subsequent computation of the centroid to obtain predictions for subjective lateral position are concepts that could in principle be applied to many types of binaural stimuli that are generated by a single source. At present, predictions of the model are largely limited to tonal stimuli because of difficulties in obtaining a tractable mathematical description of the auditory-nerve response to other types of acoustical inputs. The experiments discussed in this paper all used 500-Hz stimuli. Moss (1979) recently showed that some of the fitted parameters of the model would have to made frequency dependent to describe the subjective laterality of tones at other frequencies.

4. We plot in Fig. 2 and discuss in the subsequent sections the predicted mean and standard deviation of the IID of the acoustical pointer that most closely matches the lateral position of a target tone, rather than the perceived position itself. Smith (1979) has shown that there is a saturating nonlinear monotonic relationship between these two quantities. This transformation has no effect on the jnd predictions because changes in mean and standard deviation are compressed by the same amount as the perceptual image moves from the center of the head toward the two ears.

5. The observed dependence of the location of cue-reversal points on interaural time and intensity differences presents a natural explanation for the asymmetries with respect to time delay in amplitude-shifted time-jnd performance observed by Domnitz (1973) and Domnitz and Colburn (1977). While Domnitz (1973) had suggested that these asymmetries were observed because combinations of interaural parameters in which the louder side was lagging in time were less "physically natural," we believe that poor interaural time discrimination performance will be obtained whenever a measurement is taken near any cue-reversal point, regardless of whether the interaural time and intensity differences tend to reinforce or cancel one another. (Of course, the ITDs and IIDs producing cue reversals are all unnatural, whether reinforcing or cancelling.)

6. Data from individual trials of experiments measuring subjective laterality by Sayers (1964), Domnitz and Colburn (1977), and Yost (1981) differ somewhat. As the interaural time delay is increased to the point at which

a tonal target is interaurally out of phase, subjects in Sayers' and Yost's experiments reported an image that moved steadily toward one of the ears. The trial-by-trial data of Domnitz and Colburn imply an image that moves out toward the ear and returns to the midline as the out-of-phase point is approached. Possible reasons for the discrepancies in these data trends are discussed in Stern and Colburn (1978). Cue reversals in interaural time-discrimination experiments (discussed in Sec. II-A) support Domnitz and Colburn's description. If subjects in the time-jnd experiments made their judgments on the basis of images such as those reported by Sayers and Yost, the data would not exhibit the cue reversal phenomenon.

7. We compare relative (rather than absolute) discrimination performance to the corresponding data, because the exact nature of several arbitrarily-specified features of the model affects predicted absolute, but not relative, performance.

8. The seemingly-comprehensive data of Fig. 3 may be misleading in that they represent a composite from several experiments. In each experiment the measured time jnds of several different subjects (with presumably different cue-reversal points) have been averaged.

9. The profound qualitative differences between the time- and amplitude-discrimination data argue against any theory of binaural perception that features a peripheral intensity-to-time conversion as the sole time-intensity interaction. If the interaural intensity difference of a binaural tone were actually monotonically converted into an equivalent time delay, the poor time-discrimination performance observed for some stimulus conditions would imply that poor amplitude-discrimination performance should be observed for some corresponding set of stimuli, contrary to the data.

10. We refer to combinations of interaural time and intensity differences in which the more intense signal is leading in time as "reinforcing" because if the magnitude of the interaural time delay is less than about 300 μs (for 500-Hz tones) each interaural difference presented by itself would tend to move the perceptual image toward the same side of the head. Similarly, a "cancelling" combination of the interaural parameters is one in which the more intense signal is lagging in time.

11. The task in coherent masking experiments is actually one of interaural discrimination rather than binaural detection. For example, in tone-on-tone masking experiments the subjects must, in effect, distinguish the binaural masker tone from a second tone with an ITD and IID created by the sum of the target and masker. When the target-to-masker phase is 0 degrees, the target-plus-masker complex differs from the masker alone in interaural intensity, and not in time delay; when target-masker phase is 90 degrees the target-plus-masker complex differs from the masker alone in interaural time delay, but not in interaural intensity. For most other target-masker phases the ITD and IID of the combined target and masker vary with the target-to-masker intensity ratio according to a nonlinear relationship that is also nonmonotonic for some values of target-masker phase between 90 and 180 degrees. If target and masker are in the $N0S\pi$ configuration, the ITD and IID of the combined target and masker reinforce one another

when the target-masker phase is between 0 degrees and 90 degrees, and cancel one another with a target-masker phase between 90 degrees and 180 degrees.

12. Specifically, we assumed a linear dependence of the intensity-weighting function $M_I(\alpha_s)$ on the IID α_s of the stimulus (which is valid because α_s is always of small magnitude in these experiments), and chose the proportionality constant to fit the measured relative NOSπ thresholds at target-to-masker phase angles of 0 and 90 degrees for each of the three subjects. (This is equivalent to assuming a different time-intensity trading ratio for each subject.)

13. Specifically, a decision variable related to the "time image" can be obtained by computing the centroid of the unweighted timing function $L_T(\tau)$ of the position-variable model. The secondary image described by the subjects in the Ruotolo et al. (1979) experiment could be related (at least qualitatively) to the centroid of the model's intensity-weighting function $L_I(\tau)$. A decision variable related to the ambiguous images that may appear in the two ears when an interaurally out-of-phase tone is presented could be obtained from the position-variable model by computing the modes (rather than the centroid) of the position function $L_P(\tau)$.

FIGURE CAPTIONS

Fig. 1. Generation of position functions $L_P(\tau)$ for 500-Hz tone with +500-μs interaural time delay. The timing function, $L_T(\tau)$ is shown in (a), plotted assuming that all fibers are synchronized to the stimulus tone. In (b) and (c) we show the generation of the position function for a reinforcing (right leading and louder) combination of time and intensity differences. The position function $L_P(\tau)$ shown in (c) is the product of the timing function in (a) and the intensity function $L_I(\tau)$ in (b). Similarly, in (d) and (e) we show the generation of the position function for a canceling (right leading, left louder) combinaion of interaural time and intensity differences. For these stimulus conditions $L_P(\tau)$ in (e) is the product of $L_T(\tau)$ in (a) and $L_I(\tau)$ in (d). In (c) and (e) $\hat{P}$, the centroid of $L_P(\tau)$, is indicated by the vertical line. Note that in (a), (c), and (e) we plot the expected value of random functions, while the functions in (b) and (d) are deterministic. All functions are plotted using an arbitrary vertical scale, and for reasons of clarity we use intensity functions $L_I(\tau)$ that are considerably more narrow than those used in the actual computations.

Fig. 2. Predicted means (a) and standard deviations (b) of an interaurally in-phase pointer tone required to match the laterality of a 500-Hz test tone with interaural intensity difference α_s and interaural time delay τ_s. Parameter values of the position-variable model used to obtain these predictions are specified in Stern and Colburn (1978).

Fig. 3. Comparison of predicted and observed interaural ime jnds for equal-amplitude 500-Hz binaural tones as a function of reference interaural time delay with data from four experiments. Data from Yost (1974, ◆), Hershkowitz and Durlach (1969a, ■), Domnitz (1973, ⬬), Domnitz and Colburn (1977, ●), and Moss (1979, ▲). Predictions and data are plotted as ratios to the time jnd obtained with zero time and intensity differences, which is approximately 10 μs, using the nomenclature of Domnitz and Colburn (1977). The open data points indicate a reversal in direction of the lateralization cue. Moss's subjects reportedly used cues other than position for time delays of large magnitude. These points are indicated by partially filled symbols. The predictions of the model are indicated by the smooth curve, which is solid for predicted cues in the normal direction and broken for time delays in which a reversal in direction of the lateralization cue is predicted.

Fig. 4. Comparison of predicted and observed interaural time jnds for 500-Hz tones presented with a 20-dB interaural amplitude difference. Data for three subjects

replotted from Domnitz and and Colburn (l977). Predictions and data are plotted as ratios to time jnd obtained with zero time and intensity differences. The open points indicate a reversal in direction of the lateralization cue. Predictions of the model are indicated by the smooth curves, as in Fig. 3.

Fig. 5. Comparison of predicted and observed interaural amplitude jnds for equal-amplitude tones (filled symbols and solid curve) and 20-dB amplitude-shifted tones (open symbols and broken curve). Data are replotted from Rowland and Tobias (1967, ●), Hershkowitz and Durlach (1969, ▲), and Domnitz and Colburn (1977, ■). The data and predictions are plotted as ratios to the amplitude jnd obtained with zero time and intensity differences.

Fig. 6. Comparison of predicted and measured tone-on-tone masking thresholds for three subjects and three target-to-masker phase angles in the configurations of $N0S\pi$ (circular data symbols and solid predicted curves) and $N\pi S0$ (square data symbols and broken predicted curves). Data from Yost, Nielson, Tanis, and Bergert (1975). Unfilled symbols indicate data points that were used to fit free parameters of the model. Each subject's predictions and data are plotted relative to the $NOS\pi$ thresholds with 0 degrees target-to-masker phase.

Fig. 7. Comparisons of predictions and data for coherent-masking experiments by Jeffress and McFadden (1971) for two subjects. The target and masker are the same narrowband-noise waveform with center frequency 500 Hz. Plotted as a function of target-to-masker phase are relative lateralization thresholds (circular symbols) and relative detection thresholds (square symbols). For each subject the relative predictions for the detection and lateralization thresholds are indicated by the solid and broken curves, respectively. For some target-to-masker phase angles between 90 and 180 degrees threshold detection or lateralization is not achieved at any target-to-masker ratio. This is indicated in the predictions by a break in the smooth curve, and in the data by an arrow toward large target levels. Unfilled symbols indicate data points that were used to fit free parameters of the model.

Fig. 8. Comparison of predictions and data for the "α-sweep" experiment of Jeffress and McFadden (1971). The percentage of consistent lateralizations at a fixed target-to-masker ratio is plotted as a function of the target-to-masker phase angle. Predictions and data are plotted for Subjects HE (circular data symbols and solid curves) and WR (square data symbols and broken curves).

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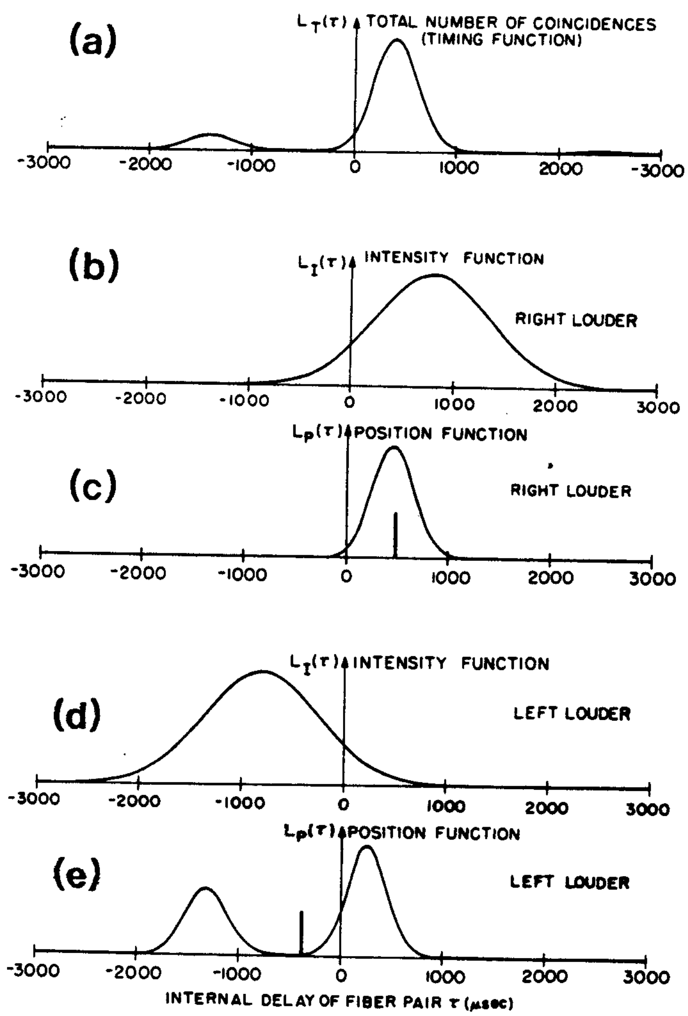
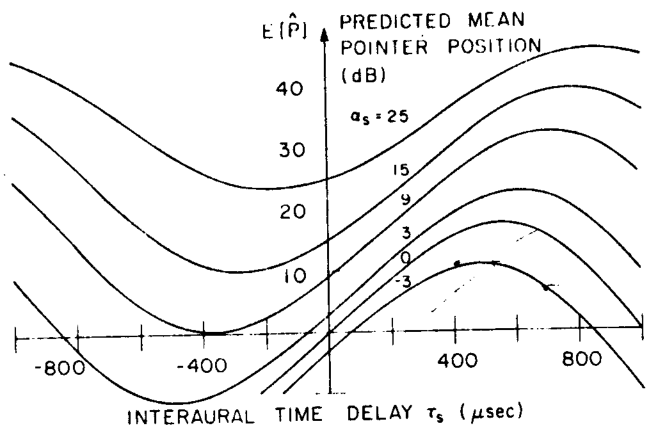
FIG. 1



(a)
$L_T(\tau)$ TOTAL NUMBER OF COINCIDENCES (TIMING FUNCTION)
-3000 -2000 -1000 0 1000 2000 -3000
(b)
$L_I(\tau)$ INTENSITY FUNCTION
RIGHT LOUDER
-3000 -2000 -1000 0 1000 2000 3000
$L_P(\tau)$ POSITION FUNCTION
(c)
RIGHT LOUDER
-3000 -2000 -1000 0 1000 2000 3000
$L_I(\tau)$ INTENSITY FUNCTION
(d)
LEFT LOUDER
-3000 -2000 -1000 0 1000 2000 3000
$L_P(\tau)$ POSITION FUNCTION
(e)
LEFT LOUDER
-3000 -2000 -1000 0 1000 2000 3000
INTERNAL DELAY OF FIBER PAIR τ (μsec)

FIG. 2

(a)


E[P̂]
PREDICTED MEAN POINTER POSITION (dB)
40
30
20
10
$a_s = 25$
15
9
3
0
-3
-800
-400
400
800
INTERAURAL TIME DELAY τ_s (μsec)

(b)

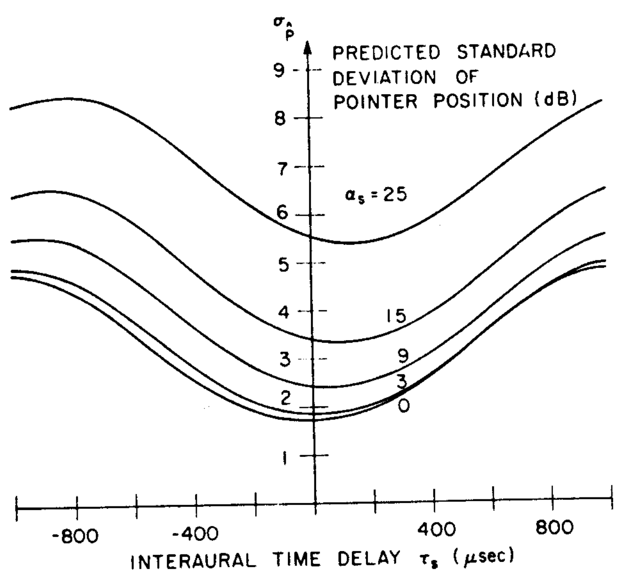
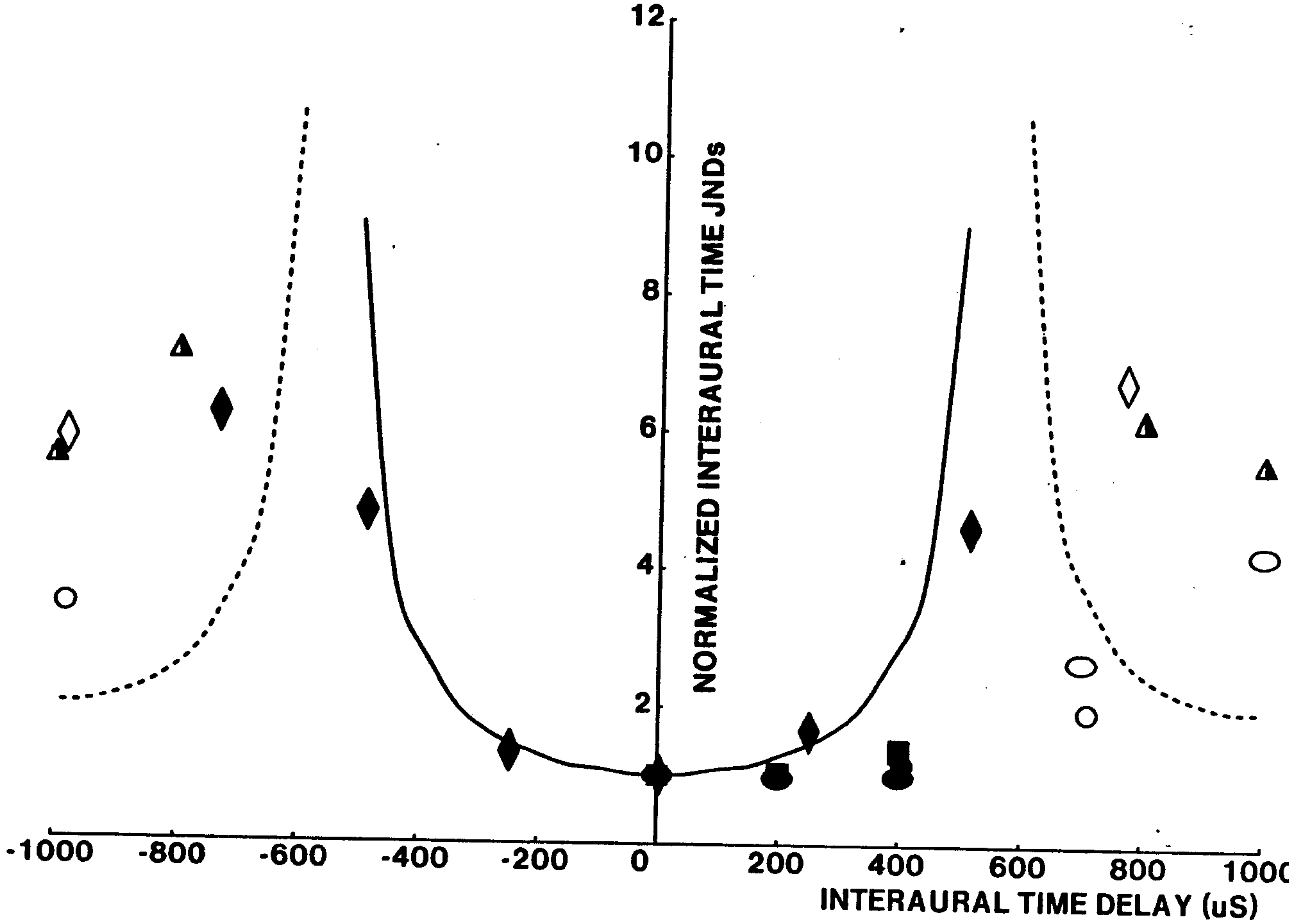
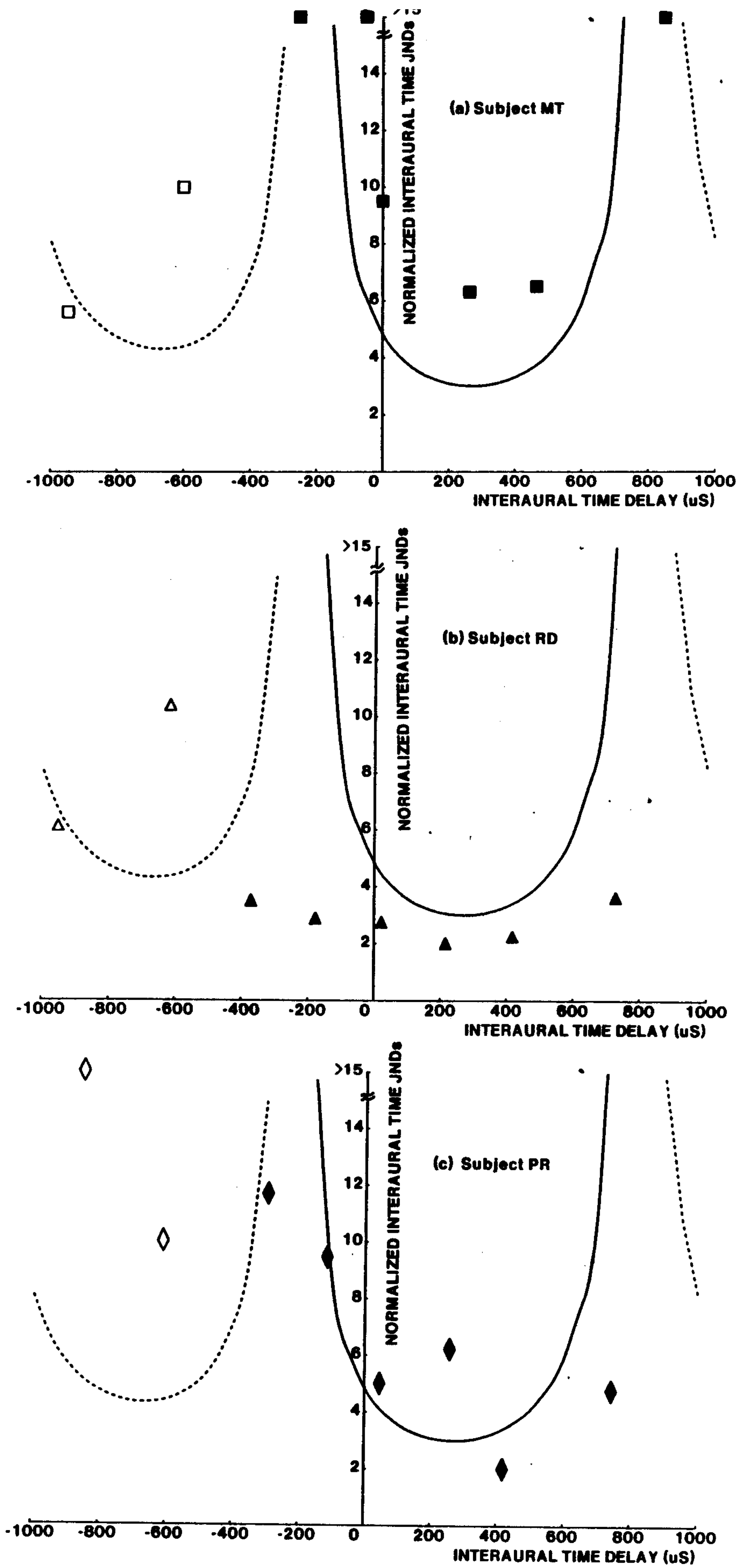

$\sigma_{\hat{P}}$
PREDICTED STANDARD DEVIATION OF POINTER POSITION (dB)
9
8
7
6
5
4
3
2
1
$a_s = 25$
15
9
3
0
-800
-400
400
800
INTERAURAL TIME DELAY τ_s (μsec)

FIG. 3



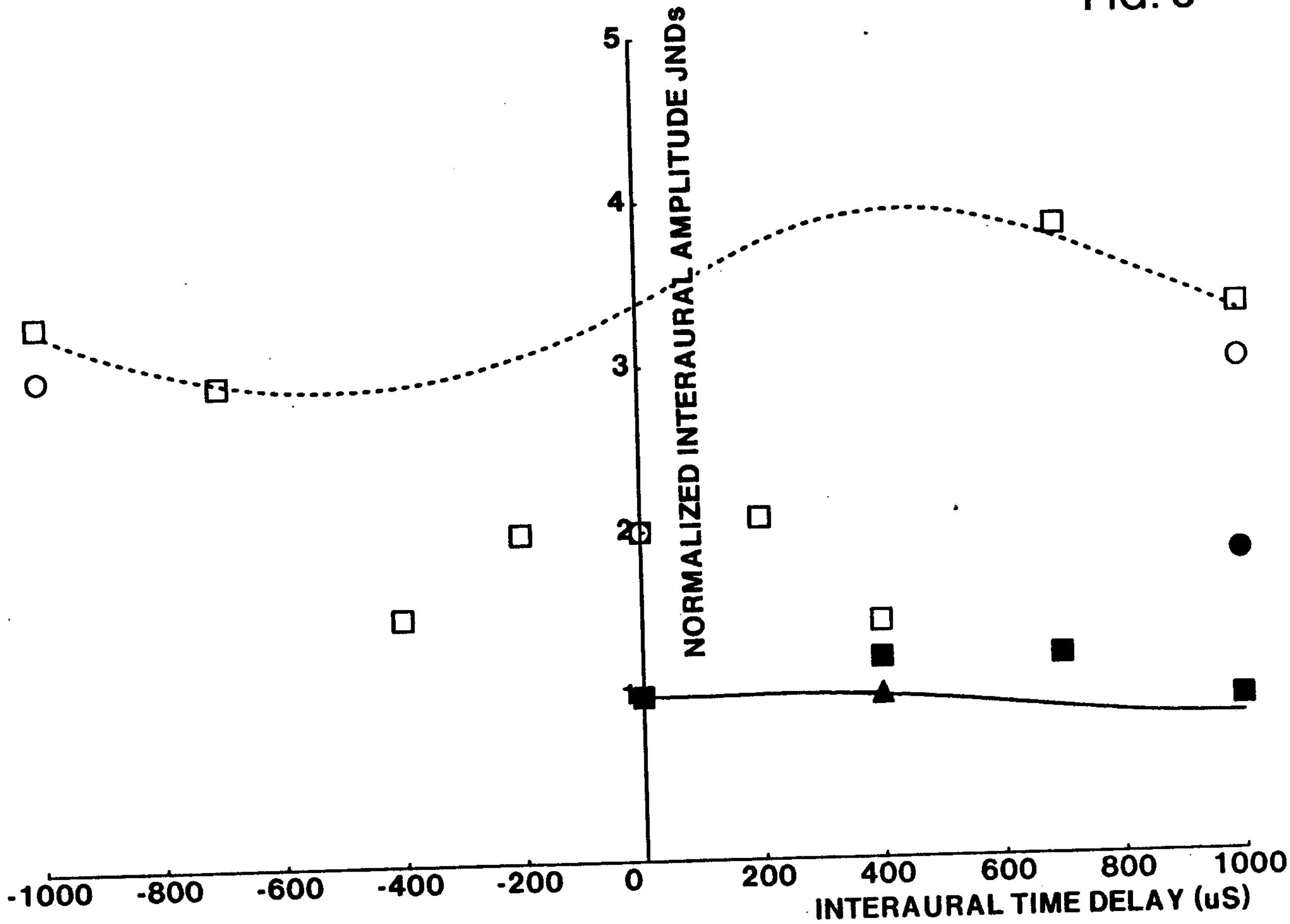
12
10
8
6
4
2
NORMALIZED INTERAURAL TIME JNDs
-1000
-800
-600
-400
-200
0
200
400
600
800
1000
INTERAURAL TIME DELAY (uS)



(a) Subject MT
(b) Subject RD
(c) Subject PR
NORMALIZED INTERAURAL TIME JNDs
INTERAURAL TIME DELAY (uS)
>15
14
12
10
8
6
4
2
-1000
-800
-600
-400
-200
0
200
400
600
800
1000

FIG. 4

FIG. 5



NORMALIZED INTERAURAL AMPLITUDE JNDs
5
4
3
2
1
-1000
-800
-600
-400
-200
0
200
400
600
800
1000
INTERAURAL TIME DELAY (uS)

FIG

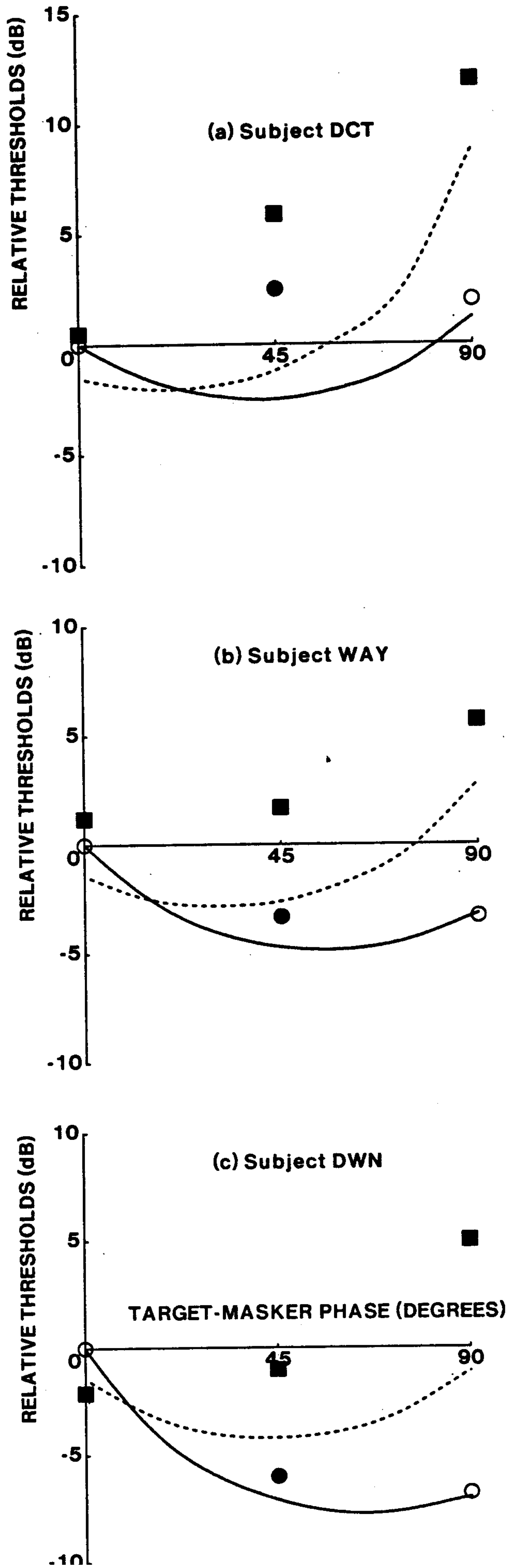

(a) Subject DCT
RELATIVE THRESHOLDS (dB)
15
10
5
0
-5
-10
45
90
(b) Subject WAY
RELATIVE THRESHOLDS (dB)
10
5
0
-5
-10
45
90
(c) Subject DWN
RELATIVE THRESHOLDS (dB)
10
5
0
-5
-10
TARGET-MASKER PHASE (DEGREES)
45
90

FIG. 7

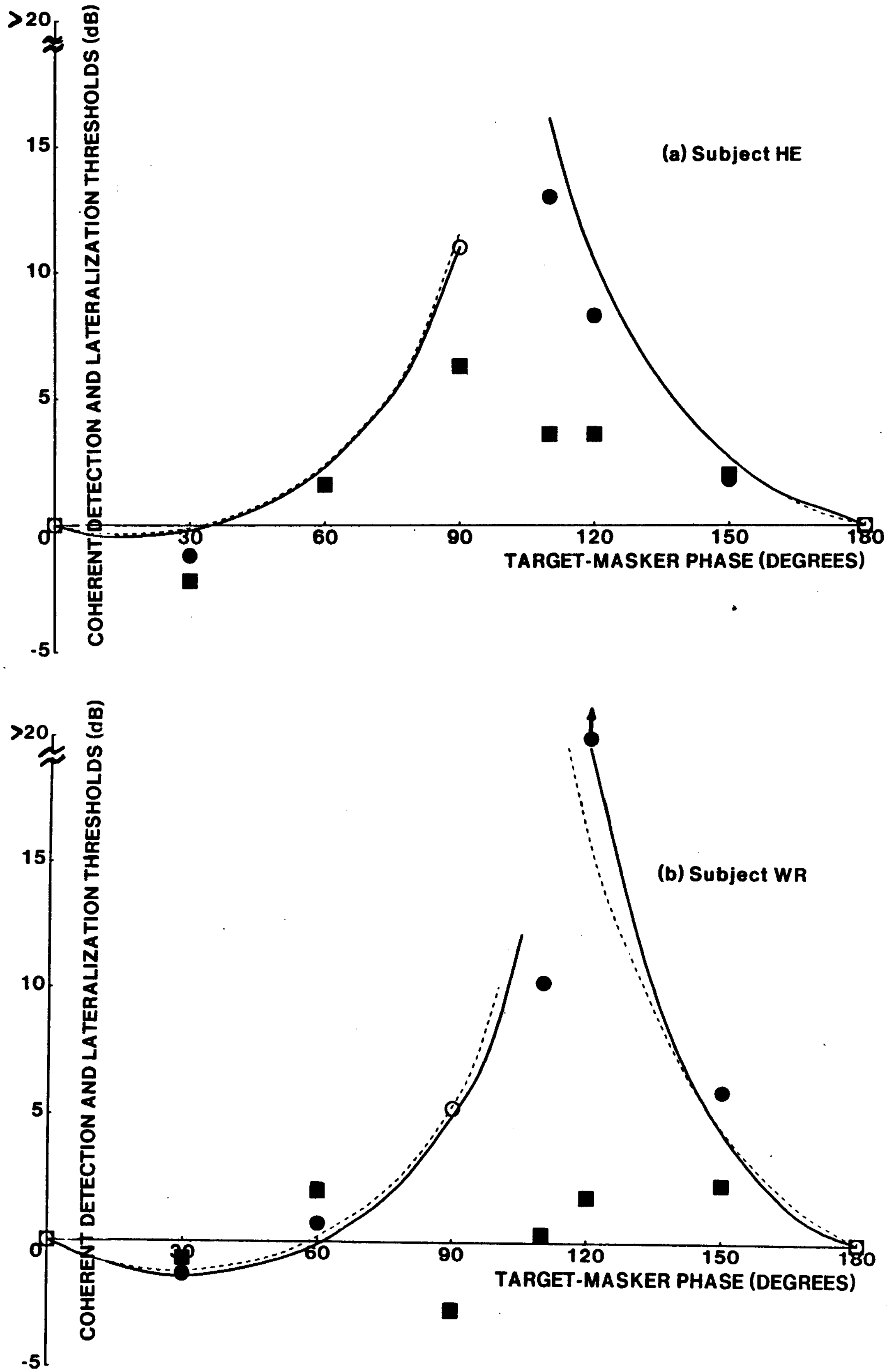
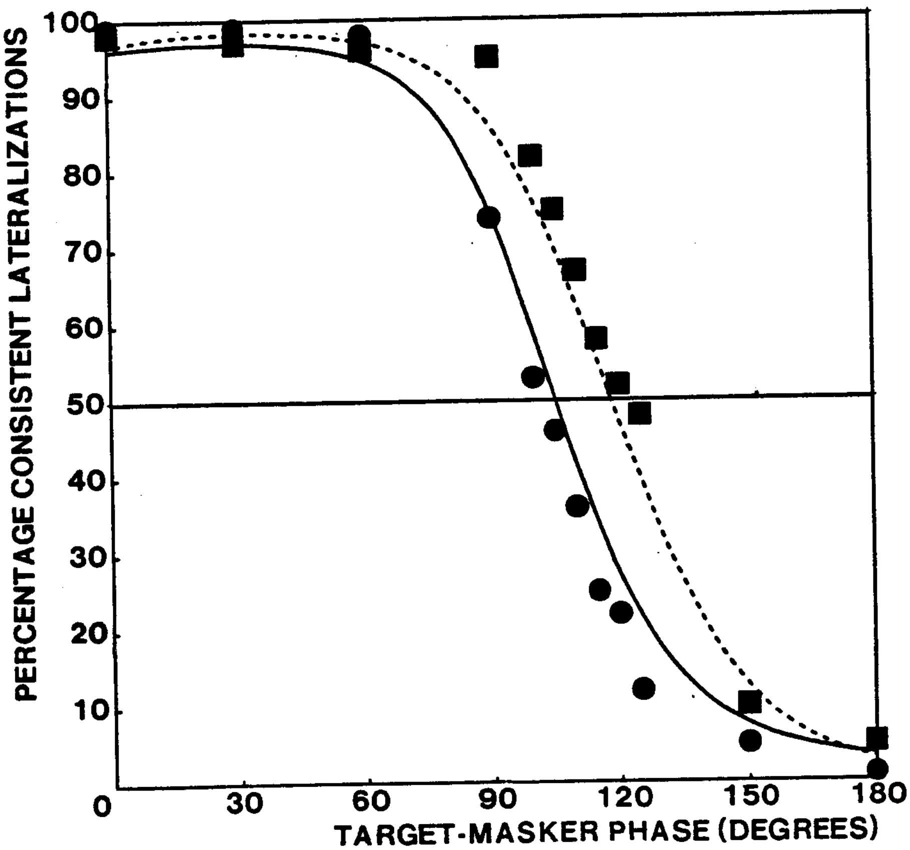

>20
15
10
5
0
-5
COHERENT DETECTION AND LATERALIZATION THRESHOLDS (dB)
(a) Subject HE
30
60
90
120
150
180
TARGET-MASKER PHASE (DEGREES)
>20
15
10
5
0
-5
COHERENT DETECTION AND LATERALIZATION THRESHOLDS (dB)
(b) Subject WR
30
60
90
120
150
180
TARGET-MASKER PHASE (DEGREES)

FIG. 8


PERCENTAGE CONSISTENT LATERALIZATIONS
100
90
80
70
60
50
40
30
20
10
0
30
60
90
120
150
180
TARGET-MASKER PHASE (DEGREES)