Lateralization Predictions for High-Frequency Binaural Stimuli

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Revised Abstract

The position-variable model [R.M. Stern, Jr. and H.S. Colburn, J. Acoust. Soc. Am. **64**, 127-140 (1978), G.D. Shear and R.M. Stern, J. Acoust Soc. Am. **81**, S27 (A) (1987)] is extended to describe the subjective lateral position of amplitude-modulated tones and bandpass noise, as well as other complex stimuli that are presented within spectral regions at which the binaural system appears to be unable to make use of cycle-by-cycle interaural temporal differences. Predictions of the model are based on the centroid of the crosscorrelation of the hypothetical auditory-nerve response to the stimuli, which is either calculated using analytical techniques or simulated numerically. The model of auditory-nerve activity, which is typically used to describe the response to stimuli at lower frequencies, also extracts envelopes of higher-frequency stimuli, as discussed previously by Colburn and Esquissaud. This information appears to be useful in predicting the lateral position of such high-frequency stimuli. Preliminary results indicate that the model is able to describe most of the ways in which the laterality of high-frequency AM tones and bandpass noise with low-frequency envelopes depends on modulation frequency, carrier frequency, and other stimulus parameters. The model also predicts the "dominant region" effect (describing the relative salience of interaural temporal cues at different frequencies), as well as counterintuitive reversals in lateralization of rectangularly-modulated bandpass noise stimuli. Important results not yet described by the model include the specific carrier frequency at which AM tones exhibit the greatest laterality with a fixed waveform delay, and the relative laterality of high-frequency AM tones and bandpass noise with narrow bandwidth. [Work supported by NSF.]

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INTRODUCTION

The position-variable model of binaural interaction describes and predicts the lateral position of a binaural signal by computing the centroid of the interaural cross-correlation of the weighted auditory-nerve response to the stimuli. This model was originally developed primarily to describe stimuli at about 500 Hz. We describe in this poster some very modest extensions to the model that enable it to describe phenomena over a much broader range of stimulus frequencies, and we compare various predictions of the extended model to the corresponding experimental results.

Three classes of modifications were needed in order to extend the model to higher frequencies. First, it is necessary to make the function describing the distribution of interaural delays of the fiber pairs frequency dependent which is discussed by (Shear, 1987). Shear (1987) also describes a simple modification to the description of auditory-nerve activity that enables the model to extract low-frequency envelopes of high-frequency stimuli, which in turn is needed to enable the model to describe high-frequency stimuli. A third type of (as yet unimplemented) modification is also needed to enable the model to emphasize interaural delays at which there is consistent stimulation over a range of frequencies. This has been important for black-box models of binaural hearing such as the weighted image model (Stern, et al, 1988).

In this talk we will briefly review of the structure of the position-variable model. We will then provide a few simple examples of the kinds of interaural cross-correlation functions that are obtained from stimuli typically used in binaural lateralization experiments. Finally, we will compare the results of several experiments describing the lateral position of high-frequency and complex stimuli to the correpsonding theoretical predictions. We will consider three broad classes of these experiments: the "dominant region" experiment by Raatgever (1980, 1986), a series of phenomena concerned with the lateralization of amplitude-modulated tones and bands of noise (such as the experiments of Henning (1974, 1980, 1983), McFadden and Pasanen (1976), Nuetzel and Hafter (1976, 1981) and Bernstein and Trahiotis (Bernstein and Trahiotis, 1985a, 1985b; Trahiotis and Bernstein, 1986), and the lateralization of gated bandpass-noise stimuli such as those described by Hafter and Shelton (Shelton, *et al.*, 1981, Hafter *et al.*, 1990).

I. REVIEW OF THE POSITION-VARIABLE MODEL OF BINAURAL INTERACTION

The position-variable model (Colburn, 1973; Stern and Colburn, 1978) describes the subjective lateral position of simple stimuli in terms of putative discharge patterns of fibers of the auditory nerve. The model includes a characterization of the peripheral auditory-nerve representation of a sound and a characterization of the type of central processing the peripheral information undergoes. The model for auditory-nerve activity (shown in block-diagram form in the upper panel of Fig. 1) consists of a bandpass filter followed by an automatic gain control device, a nonlinear rectifier, a lowpass filter, and finally a mechanism that generates firing times in a probabilistic fashion governed by the mathematics of non-homogenous Poisson processes. The instantaneous rate of firing of the Poisson processes are assumed to be proportional to the continuous output of the lowpass filter. The bandpass filter is intended to represent the frequency andalysis of the cochlea and the peripheral auditory system. The nonlinear rectifier reflects the need for the rate that drives the Poisson-process generator to be a positive one, and the lowpass filter is included to characterize the inability of the peripheral auditory system to track the fine structure of high-frequency stimuli. One of the consequences of this bandpass filter-nonlinear rectifier-lowpass filter structure is that the system as a whole achieves envelope processing of high frequency complex stimuli (*i.e.* the output of the model reflects the low-frequency envelopes but not the high-frequency fine structure of high-frequency complex stimuli). The predictions in the present paper use the perpheral filtering model adopted by Siebert (1968) and Colburn (1973), a halfwave power-law rectifier, and a characterization of the lowpass filter motivated by physiological data of Johnson (1974). This was largely done for reasons of analytical tractability, and these characterizations do not describe several well-known physiological phenomena, such as the relatively broad tails of the turning curves of high-frequency auditory-nerve fibers, two-tone suppression phenomena, and the refractory period of several milliseconds observed in the actual physiological measurements of the auditory-nerve response to simple sounds. We already know that the lack of refractoriness can be a significant problem in modeling the statistics of the response of these models to noise stimuli, and the other various omissions and simplifications may be problematical for other stimuli as well.

The model for central processing was first proposed by Colburn (1977) and is summarized by the lower panel of Fig 1. We assume that pairs of auditory-nerve fibers with identical characteristic frequencies are presented to a mechanism that counts coincidences in arrival times from these fibers after the fibers from one ear has been delayed by a specific fixed amount indicated as τ_m in the figure. Hence, the outputs of these units are characterized by two parameters: the characteristic frequency of the unit, and the so-called "characteristic delay". At a particular characteristic frequency, the average value of the number of coincidences recorded per unit time plotted as a function of the characteristic delay is proportional to the cross-correlation function of the stimuli to the two ears, after they undergo the bandpass filtering, rectification, and lowpass filtering operations. This display of information may be regarded as an implementation of the running cross-correlation operation proposed by Sayers and Cherry (1957), using a neural mechanism inspired by Jeffress (1948).

We believe that it is frequently insightful to think about the processing of binaural stimuli in terms of the outputs of this network of coincidence counters, in terms of the two parameters that specify them: interaural delay and characteristic frequency. We will describe some of the types of cross-correlation functions that are produced by the model when presented with various different kinds of binaural stimuli, considering in particular the response to pure tones, amplitude-modulated tones, and bandpass noise.

II. CROSS-CORRELATION FUNCTIONS PRODUCED BY THE POSITION-VARIABLE MODEL

Lateralization of pure tones. It is helpful to first consider how the general cross-correlation model might be useful in lateralizing pure tones, even though experiments considered in this talk deal with more complex stimuli. The next slide (Fig. 2) shows a plot of the relative number of coincidences as a joint function of the characteristic delay (which is plotted in ms along the horizontal axis), and characteristic frequency (which is plotted in Hz along the oblique axis). This stimulus in this slide is a pure tone of 500 Hz presented with an interaural time delay (ITD) of 500 μs. The upper panel shows the number of coincidences as a function of these two parameters directly. The lower panel shows the result of weighting the coincidences in the upper panel by a function $p(\tau, f)$ that is believed to represent the relative number of fiber pairs that are present at a given characteristic frequency. The weighted function in the lower panel indicates the total number of coincidences that would be observed over all fiber pairs with a given characteristic frequency and characteristic delay. It is clear that at each characteristic frequency there is a distinct maximum in the cross-correlation function at a value of internal delay that is close to that of the original interaural delay of the stimulus. The next slide (Fig. 3) shows the function $p(\tau, f)$ actual that we used to describe the distribution of internal delays of the coincidence counters as a function of frequency and characteristic delay. This function was empirically derived to predict the relative masking level differences of two types of antiphasic tone-in-noise detection stimuli, as well as the observed dependence of the lateralization of tonal stimuli with a fixed ITD on stimulus frequency (*cf.* Shear, 1987). It can be seen that the shape of the function implies that there are more units with small interaural delays than with interaural delays of greater magnitude. In addition, there are at least a small number of coincidence counters with characteristic delays that are much greater in magnitude than the "headwidth" constraint, (*i.e.*, the maximum delay that would be presented to the ears by free-field stimuli).

In all cases, the lateral position of a stimulus is predicted by computing the center of mass along the τ axis of the product of the crosscorrelation function and the weighting function $p(\tau, f)$. Quantitative predictions can also be obtained for results of interaural discrimination experiments by assuming that the position of a single image is the only cue used in performing the task.

Several phenomena that have not yet been adequately described using this formalism include the perception of images for stimuli with multiple components that can be perceived separately and the shape of perceived image of a binaural sound.

Lateralization of low-frequency bandpass noise. The next slide (Fig. 4) shows the cross-correlation patterns of narrowband noise presented with a center frequency of 500 Hz, and two different bandwidths, 50 Hz (Fig. 4a) and 800 Hz (Fig 4b). In both cases the stimuli are presented with an ITD of -1500 μs (or -1.5 ms). The response pattern for the noise with the bandwidth of 50 Hz looks very similar to the cross-correlation pattern observed when a tone at 500 Hz is presented to the listener with the same ITD (-1.5 ms) as in Fig. 3a. With greater stimulus bandwidths, however, (as in the case of the 800-Hz wide stimulus producing the cross-correlation function seen in the lower panel) the cross-correlation function exhibits a pattern in which the identity of the the true ITD becomes more obvious, because the cross-correlation function exhibits modes at internal delays of (-1.5 ms) over all frequencies. These modes collectively form a a straight ridge of the cross-correlation function that is parallel to the f-axis.

Lateralization of high-frequency amplitude-modulated tones and bandpass noise. In the next slide (Fig. 5), we illustrate the cross-correlation functions that are observed in response to high-frequency amplitude-modulated tones and to bandpass noise In the upper panel (Fig. 5a), we show the response of the model to an amplitude-modulated tone with a center frequency of 3900 Hz and a modulation frequency of 300 Hz. In the lower panel (Fig. 5b), we show the response to a slightly different stimulus: a bandpass noise with the same center frequency and a bandwidth of 600 Hz. Each stimulus is presented with an ITD of 500 μs. In both cases, we note that the response at the carrier frequency (3900 Hz) is greatly attenuated, the ITD of the stimulus can be inferred by the implicit envelope-detecting effects of the cascade combination of the bandpass filter, nonlinear rectifier, and lowpass filter in the model characterizing the processing of the peripheral auditory system. (No additional explicit envelope extraction mechanism was invoked in order to produce these plots.)

Lateralization of each of these two kinds of stimuli is dominated by the mode of the *envelope* of the corresponding cross-correlation functions, which in each of these two examples occurs at a small positive value of τ. In general, the cross-correlation models predict that lateralization of these high-frequency stimuli is dominated by the delay of the envelope of the stimuli, rather than the stimulus fine structure, which is exactly what is observed in the corresponding data.

III. PREDICTIONS OF THE EXTENDED POSITION-VARIABLE MODEL

We now compare some of the predictions of the model to the corresponding lateralization and discrimination data.

A. "Dominant Region" experiments

We first compare theoretical predictions to the "dominant region" phenomenon described by Raatgever (1980, 1986). Subjects in these experiments are typically presented a binaural stimulus with three bands of noise, with either the high- and low-frequency bands or the mid-frequency band presented with an ITD of $+T$. The overall amplitude of the mid-frequency band is incremented (relative to that of the flanking bands) by the amount ΔI that causes a given ITD in the mid-frequency band to produce the same subjective laterality (for the total stimulus) as is produced by that same ITD when presented in the two flanking bands. Figure 6a shows typical data from three subjects for this experiment and Fig. 6b shows the corresponding predictions of the little model. It is important to note that these predictions were generated using the position-variable model in the original form described above, with no explicit attempt to incorporate a mechanism to produce weighting in the "dominant region" of 400 to 900 Hz. Nevertheless, the predictions describe the form of the data quite well, and indicate that the binaural system appears to be maximally sensitive to components of stimuli in this intermediate frequency region.

We believe that the ability of the model to predict the data without any sort of explicit sort of explicit weighting mechanism is a consequence of the interaction between the cross-correlation function of the stimulus and the relative number of internal delays in the binaural system at a given internal delay (*cf.* Fig. 3b). The breadth and the separation of the modes of the cross-correlation function obtained in response to broadband stimuli such as those used by Raatgever will be inversely proportional to the characteristic frequency of the peripheral filter. At very low frequencies, the modes of the cross-correlation function for noise stimuli are broad relative to the width of the function $p(\tau,f)$. Since the cross-correlation function is multiplied by the function $p(\tau,f)$ in generating predictions, and since the cross-correlation function is much broader than the function $p(\tau,f)$ at low frequencies, the product of these two functions is dominated by $p(\tau,f)$, which of course does not depend on the ITD of the stimulus. At sufficiently higher frequencies, many modes of the cross-correlation function will appear within the central region of $p(\tau,f)$, so the product function will be relatively unaffected also as a single mode leaves or enters the central region of $p(\tau,f)$. We expect to find the greatest dependence on the ITD of the stimulus of the centroid of the product of the cross-correlation function and $p(\tau,f)$ to occur at an intermediate range of frequencies in which the breadth of the main lobe of the cross-correlation function is roughly one half the width of the central area of the function $p(\tau,f)$. This occurs at frequencies of about 700 Hz.

To summarize, we strongly believe that there is no "dominant region" *per se* in the binaural system. We believe instead that the observations of Raatgever *et. al.* are a natural consequence of the distribution of relative delays of the coincidence-counting units in the binaural system.

B. Lateralization of AM tones and bands of noise

Several experimenters measured the lateralization of AM tones and bandpass noise as a function of the carrier frequency, modulator frequency, interaural carrier frequency difference, different types of ITD of the stimulus, and other stimulus parameters. Lateralization was measured either directly using subjective methods *e.g.* Bernstein and Trahiotis, 1985a) or by considering the percentage of consistent lateralization estimates in a task (*e.g.* Henning, 1983). In some cases, lateralization performance is inferred from results in objective discrimination experiments (*e.g.* Nuetzel and Hafter, 1981).

Theoretical predictions were obtained by computing the centroid of the cross-correlation function [after weighting by $p(\tau,f)$] over characteristic frequencies where auditory-nerve fibers from both ears are firing "actively" (*i.e.*, with fibers from both ears responding at a rate above their spontaneous rate). The *only* way that information is obtained above the low-frequency envelopes of high-frequency stimuli is from the implicit envelope extraction that takes place at the auditory periphery. This peripheral envelope extraction is a feature of the model for auditory-nerve activity. A special effort was made to consider how the predictions are affected by the assumed distribution of fiber pairs as a function of their internal delay (the function $p(\tau,f)$. Predictions were (linearly) vertically normalized to best describe the data.

Lateralization of high-frequency AM tones: Dependence on carrier frequency. We first consider the dependence of lateral position of amplitude-modulated tones on carrier frequency. Figure 7a describes data by Henning (1974) showing how the lateral position of AM tones depends on carrier frequency as a function of waveform delay. The predictions of the extended position-variable model (Fig. 7b) accurately describe the approximately-linear dependence on lateral position on the ITD. Nevertheless, the data show that maximum lateralization is observed when the carrier frequency is 3900 Hz, rather than the 2100-Hz maximum seen in the predictions. We are currently trying to better understand why the predictions describe maximum laterality at a different center frequency from the data.

Lateralization of high-frequency AM tones: Dependence on modulator frequency. Figure 8 shows the observed and predicted dependence of lateralization of AM tones on modulation frequency (also from Henning, 1974). The predictions and data agree in that maximum lateralization is observed at the intermediate modulation frequency of 300 Hz. This is probably true for reasons similar that those underlying the "dominant-region" effect of Raatgever that is discussed above. Specifically, at low modulation frequencies, the peaks of the cross-correlation function produced by the modulation are very broad, so the crfoss-correlation function is not strongly dependent on the stimulus ITD. At very high modulation frequencies (such as 1250 Hz) the modulation produces many peaks and valleys in the central region of the cross-correlation function, so varying the ITD produces very little effect on the overall centroid. It is interesting that the frequency producing maximum lateralization effect is approximately 700 Hz in the case of Raatgever's "dominant region" experiment, but only approximately 300 Hz in the case of the present experiments. We believe that these differences may provide some insight into the shape of the function $p(\tau,f)$ at higher frequencies, and we will continue to study this aspect of the data.

Lateralization of bandpass noise: Dependence on center frequency. The next slide (Figure 9) compares lateralization data by Trahiotis and Bernstein (1986) describing the dependence of bandpass noise on center frequency with the corresponding predictions. The decrease in laterality observed in both the data and predictions as the center frequency is increasedn reflects the well-known effect that low-frequency ongoing phase information is a more salient cue for lateralization than information related to interaural differences in the envelopes of high frequency stimuli. Both data and predictions show increased laterality as bandwidth is increased from 50 to 400 Hz, although the dependence of laterality on bandwidth seen in the predictions is much smaller.

Lateralization of low-frequency AM Tones: Use of envelope-based temporal differences. Figure 10a summarizes data obtained by Bernstein and Trahiotis (1985), which demonstrate the ability of the binaural system to lateralize low-frequency AM tones on the basis of the ITD of their envelopes. As can be seen, both data (Fig. 10a) and predictions (Fig. 10b) show that the lateral position for waveform ITDs between 1 and 2 ms is indeed affected by interaural differences of the envelope of the stimulus as indicated by the differences among the curves plotted for different modulation frequencies. We believe that these results indicate an ability of the binaural system to detect and respond to regions of the cross-correlation function in which the peaks show up at a consistent time delay over a range of frequencies, as discussed in Stern *et al.* (1988).

Lateralization of low-frequency transients Presented with "pure" group delays: Dependence on center frequency

Henning (1983) did a series of studies measuring the perceived lateral position of bandpass filtered transients presented with a "group delay" only. (Specifically, the stimuli were presented with a combination of ITD and interaural phase difference [IPD] such that the IPD was a linear function of frequency and equal to zero at the center frequency the stimulus.) Figure 11 shows a representative set of such measurements andalong with the corresponding predictions, obtained when the bandwidth of the stimulus was held fixed at 800 Hz, and the center frequency was varied as a parameter. We note that the predicted and observed lateral positions shift from one side of the head to the other as the center frequency is increased from 500 to about 1000 Hz. Henning interprets this phenomenon as another manifestation of the "dominant-region" phenomenon described by Raatgever, and the model probably describes this aspect of the data for the reasons discussed above. The fit of the predictions to the data is only fair for frequencies above 1000 Hz, and we are currently attempting to better understand these discrepancies between predictions and data.

Other data. We have also applied the position variable to a number of other aspects of the lateralization of amplitude-modulated tones and bandpass noise. Some of the other phenomena described by the model include the greater salience of carrier delays and waveform delays compared to modulator delays for AM tones and bandpass noise, as well as the decreased lateralization observed for AM tones when the carrier frequencies of the signals to the two ears are presented with an interaural frequency difference.

III. Lateralization of Bandpass Rectangularly-modulated Noise

A number of years ago, Shelton *et. al* (1981) first described an interesting and unexpected phenomenon concerning the lateral position of dichotic band pass noise that it subsequently multiplied by a diotic pair of rectangular gating functions. They found that when the gating functions were presented with an ITD, the gated-noise stimuli would be strongly perceived toward the ear receiving the signal with the gating function that was *lagging* in time for many combinations of stimulus parameters. These results were surprising because one of the classic tenets of binaural hearing has been that sounds presented with ITDs are perceived toward the ear receiving the signal that is leading in time.

In developing predictions for these stimuli, we determined that the cross-correlation of the gated noise is equal to the product of the cross-correlation of the input noise and the cross correlation of the gating function. This suggests a new class of ways to manipulate the cross-correlation functions of binaural stimuli.

Figure 13 compares the perceived lateral position (as estimated from the percentage of consistent lateralizations) as a function of center frequency of the bandpass noise. Frequencies for which the percent in correct lateralization is less than 50 percent represent conditions in which the stimulus is lateralized on the "wrong" side of the head. The theoretical predictions provide an excellent description of the observed data. They also correctly describe the dependence of the lateral position on the duration of the gating pulses, as well as the fact that the lateralization performance seems to be related to the low-frequency content of the binaural signals. We believe that the easiest way to understand the likely mechanism for the "illusory" reversals, and specifically the predictions of Fig. 13 is by considering how the gated-noise stimuli are likely to be represented by the binaural system. Figure 14 shows the internal cross-correlation (after multiplication by the weighting function $p(\tau, f)$) which represents the internal response of an ensemble of binaural fiber pairs the stimuli of Fig. 13 with center frequencies of 2000 Hz and 3000 Hz. These combinations of stimulus parameters were chosen because they illustrate center frequencies that produce normal and unexpected subjective lateral positions, and it can be seen that their cross-correlation functions exhibit a broad mode near the center of the internal-delay axis, but on opposite sides for the two center frequencies. The position-variable model computes the centroid along the internal-delay (τ) axis to estimate the perceived lateral position, so its predictions reflect the location of the mode of the stimulus along the τ axis.

We have also found that these data do *not* appear to be consistent with the hypothesis that lateralization is based solely on the processing of low-frequency interaural group delay. We discuss these predictions and some of their consequences extensively in Stern *et al.* (1990).

IV. SUMMARY

We obtained predictions of the extended position-variable model for a number of binaural lateralization results with high-frequency and low-frequency stimuli. We found that information about interaural time differences obtained from the present model for auditory-nerve activity is sufficient to describe most high-frequency binaural lateralization phenomena, and specifically that no additional envelope-extraction mechanism appears to be necessary. The model also describes without further modification the "dominant-region" effect of Raatgever and the counter-intuitive dependencies of the lateralization of rectangularly-modulated bandpass noise on the ITD of the gating function.

All of the above predictions were obtained by extending the position-variable model as developed to described low-frequency phenomena with minimal modification. Further improvements in the fit of the predictions to the data should be obtained by greater attention to those results that are presently not well described by the model.

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Figure 1. Block diagram of a generic model of binaural interaction used for the predictions in the forthcoming figures. (a) Functional elements used in a typical model of the auditory-nerve response to a sound. (b) Block diagram of a mechanism to record interaural coincidences of auditory-nerve activity (from Colburn, 1977a).

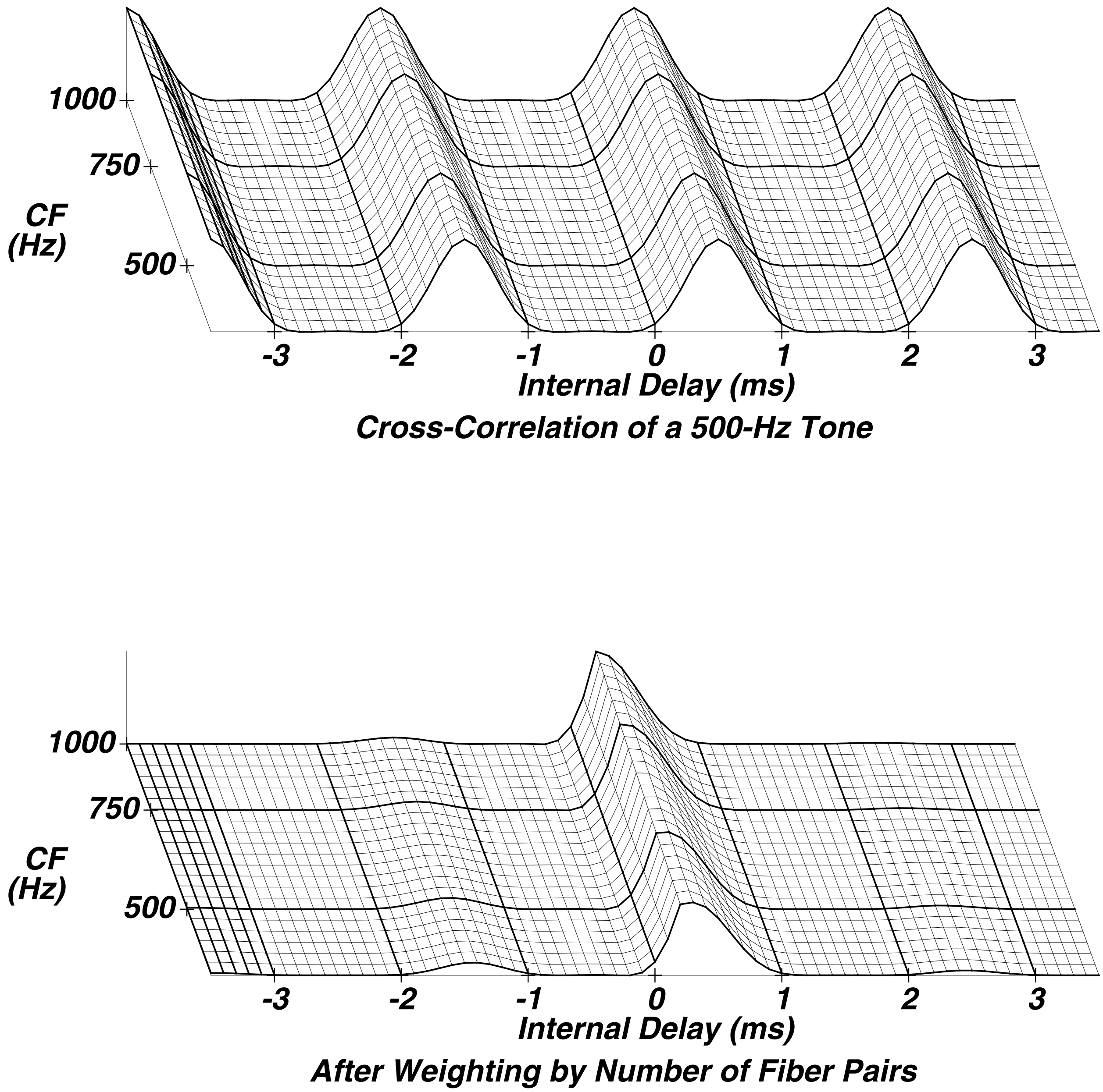


Figure 2. Cross-correlation patterns showing the response of an ensemble of binaural fiber pairs to a 500-Hz pure tone with a 500-µs ITD. (a) The original cross-correlation function. The horizontal axis indicates the internal interaural "characteristic delay" of the fiber pairs (in ms), and the oblique axis indicates the characteristic frequency of the auditory-nerve fibers (in Hz). (b) The same cross-correlation function, after multiplicative weighting by the function representing the relative number of fibers having a particular characteristic delay and characteristic frequency shown in fig. 3.

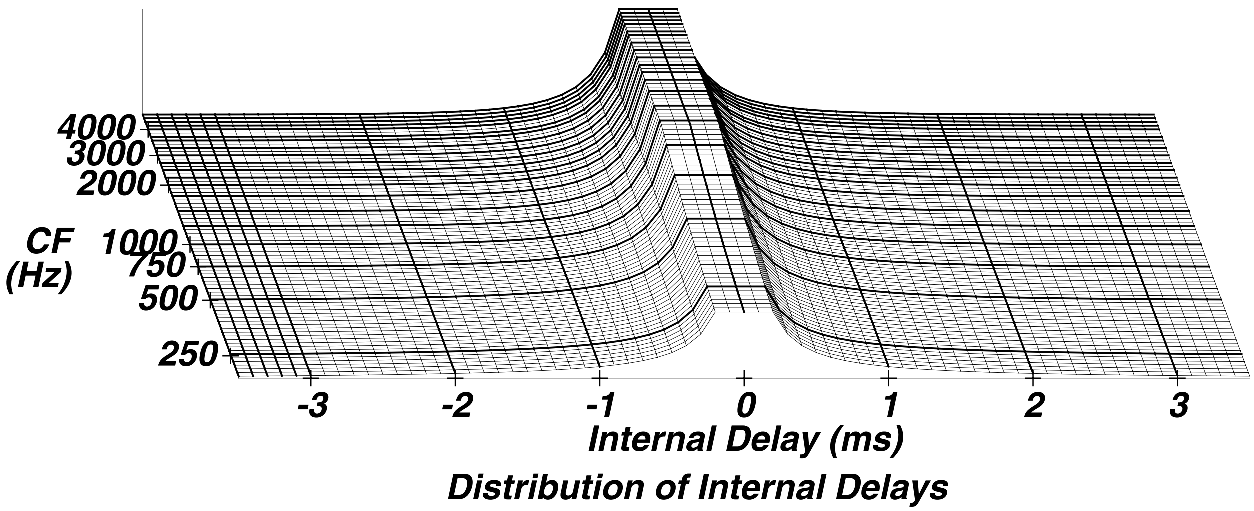
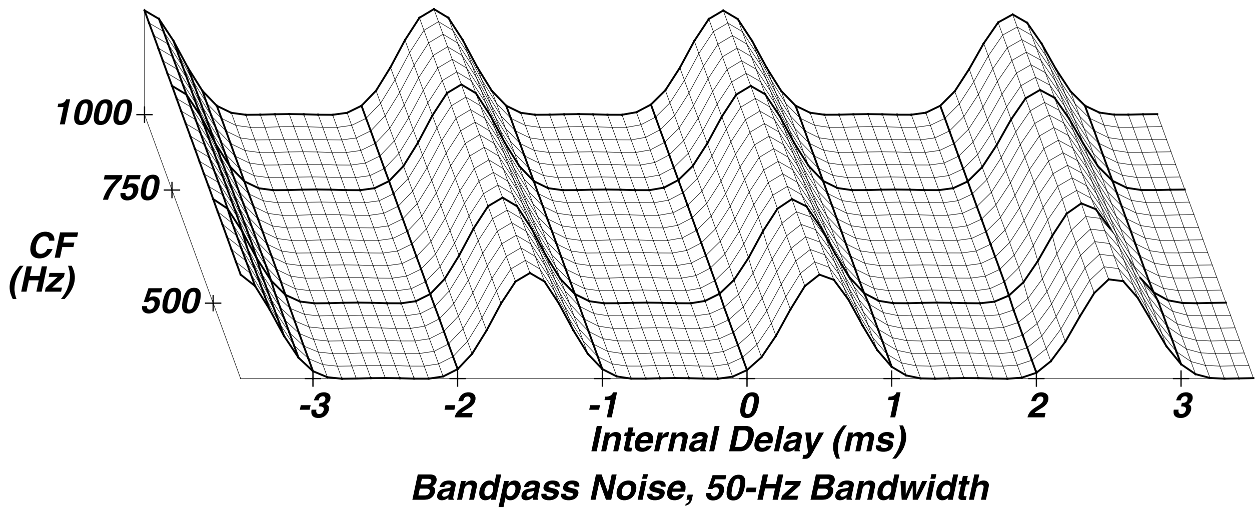


Figure 3. The assumed distribution of internal delays as a function of characteristic frequency. This function was fitted to simultaneously describe the relative masking level differences of two types of antiphasic tone-in-noise detection stimuli, as well as the observed dependence of the lateralization of tonal stimuli with a fixed ITD on stimulus frequency (Shear, 1987).



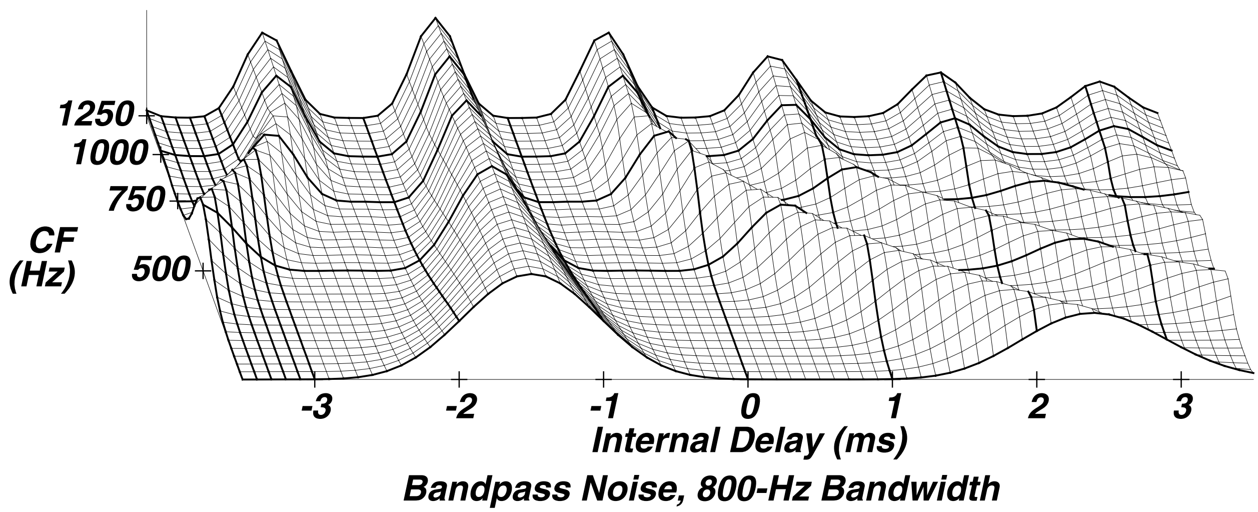
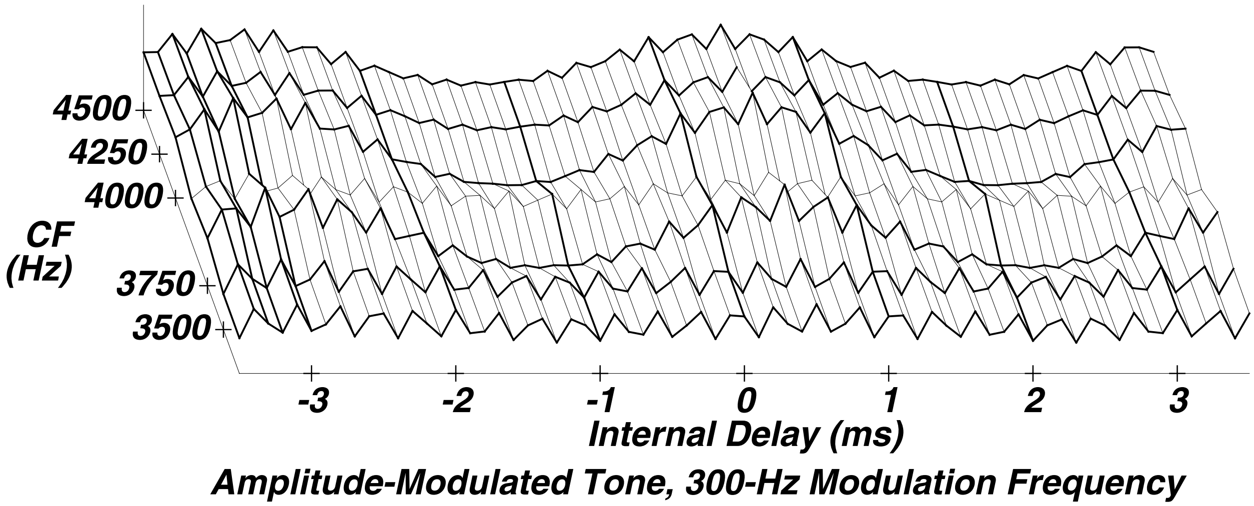


Figure 4. Cross-correlation functions showing the response of the model to low-frequency bandpass noise. (a) Response to bandpass noise with a center frequency of 500 Hz and a bandwidth of 50 Hz. The ITD in each case is -1500 μs. (b) Response to bandpass noise with a center frequency of 500 Hz and a bandwidth of 800 Hz.



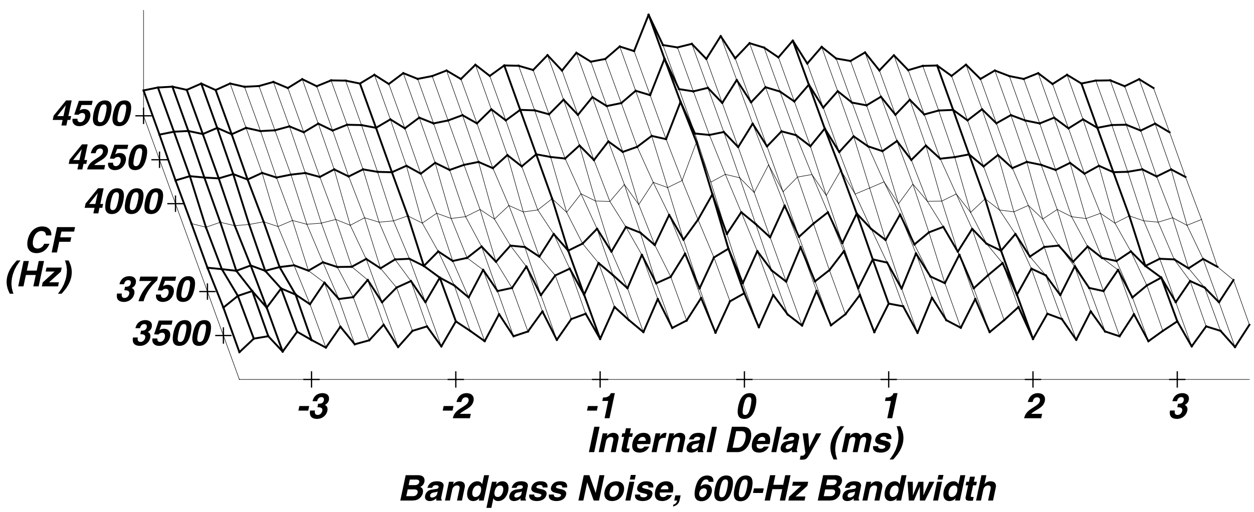


Figure 5. Cross-correlation functions showing the response of the model to amplitude-modulated (AM) tones and high-frequency bandpass noise. (a) Response to AM tones with a center frequency of 3900 Hz and a modulation frequency of 300 Hz. (b) Response to bandpass noise with a center frequency of3900 Hz and a bandwidth of 600 Hz.

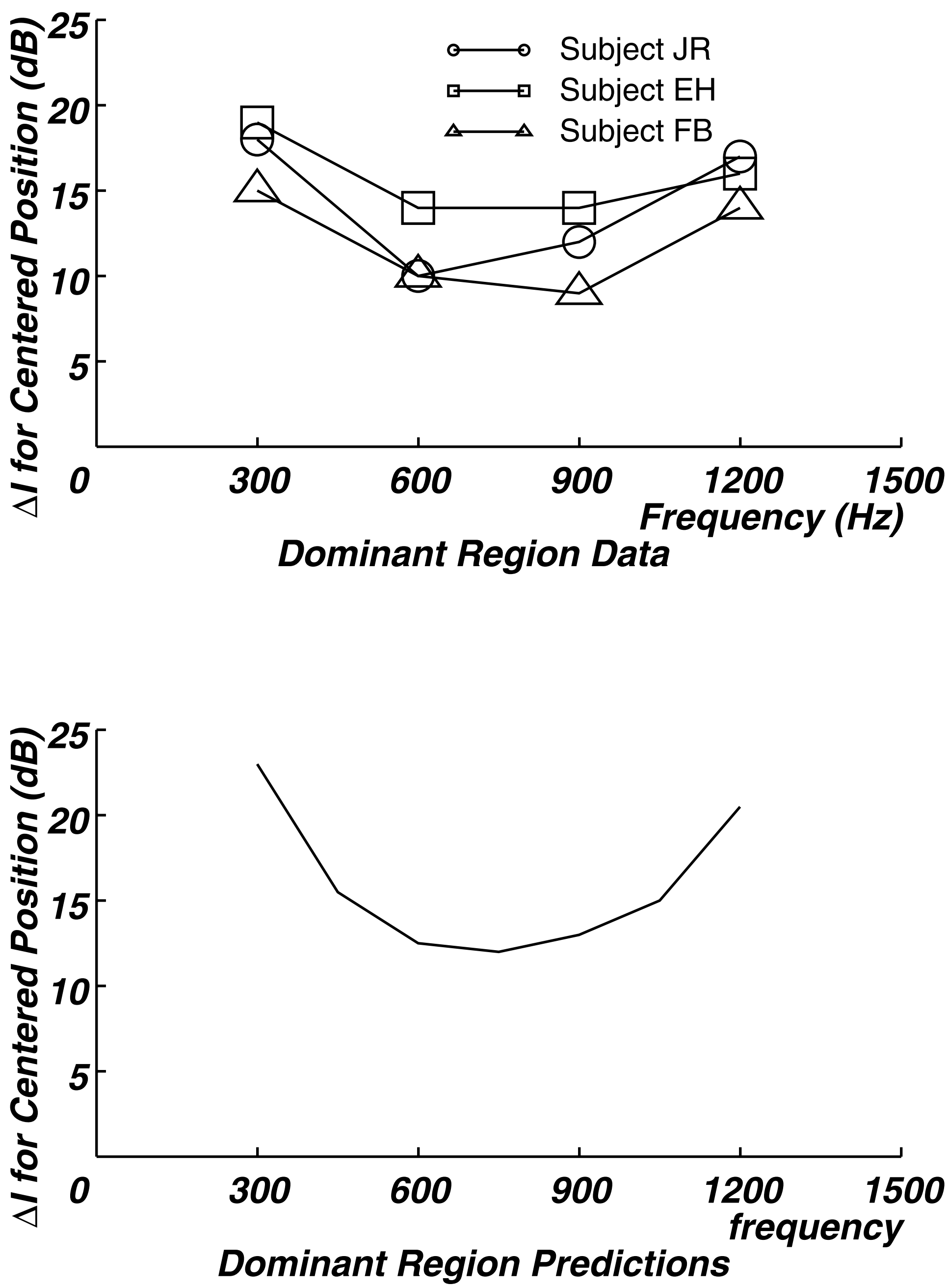


Figure 6. Comparison of data by Raatgever (1980) and theoretical predictions for experiments whose results implied the existence of a "dominant frequency region" for binaural lateralization.

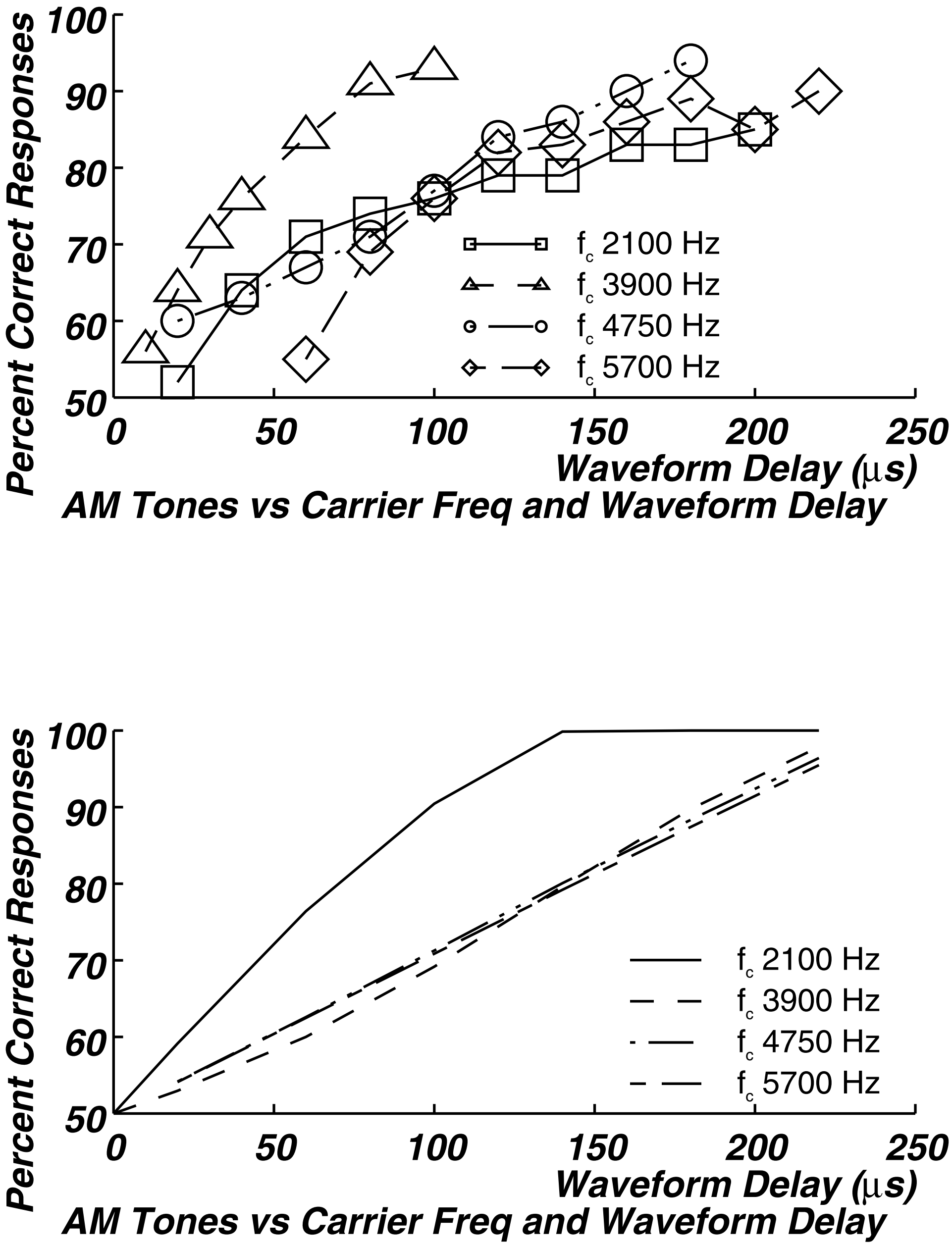
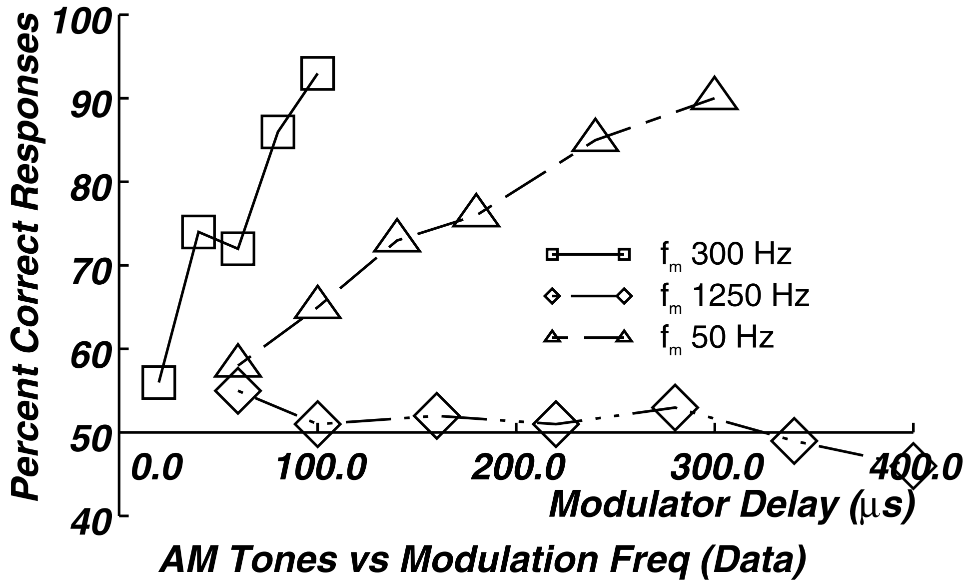


Figure 7. Comparison of data by Henning (1974) and theoretical predictions describing the dependence of the perceived laterality of amplitude-modulated tones on carrier frequency and waveform delay.



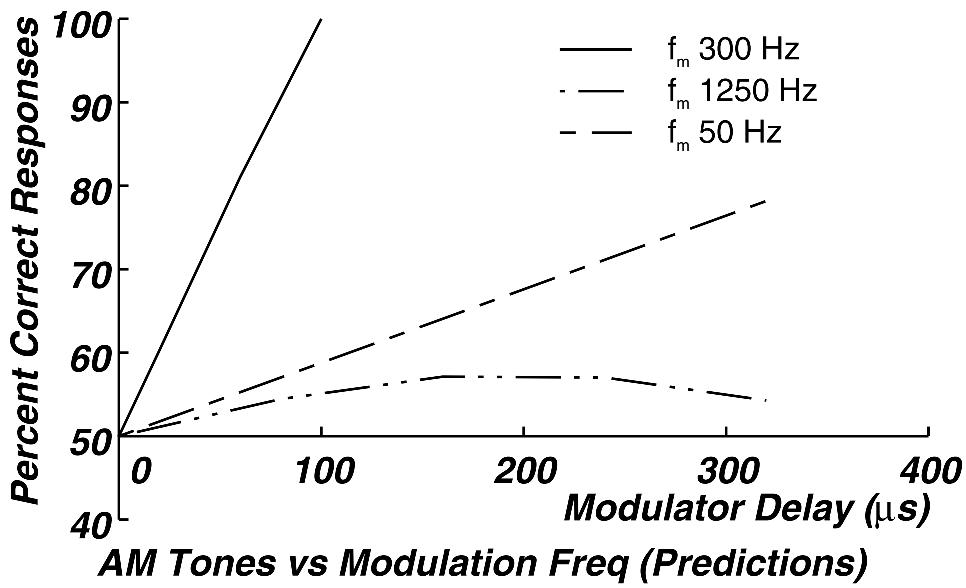


Figure 8. Comparison of data by Henning (1974) and theoretical predictions describing the dependence of the perceived laterality of amplitude-modulated tones on modulator frequency and modulator delay.

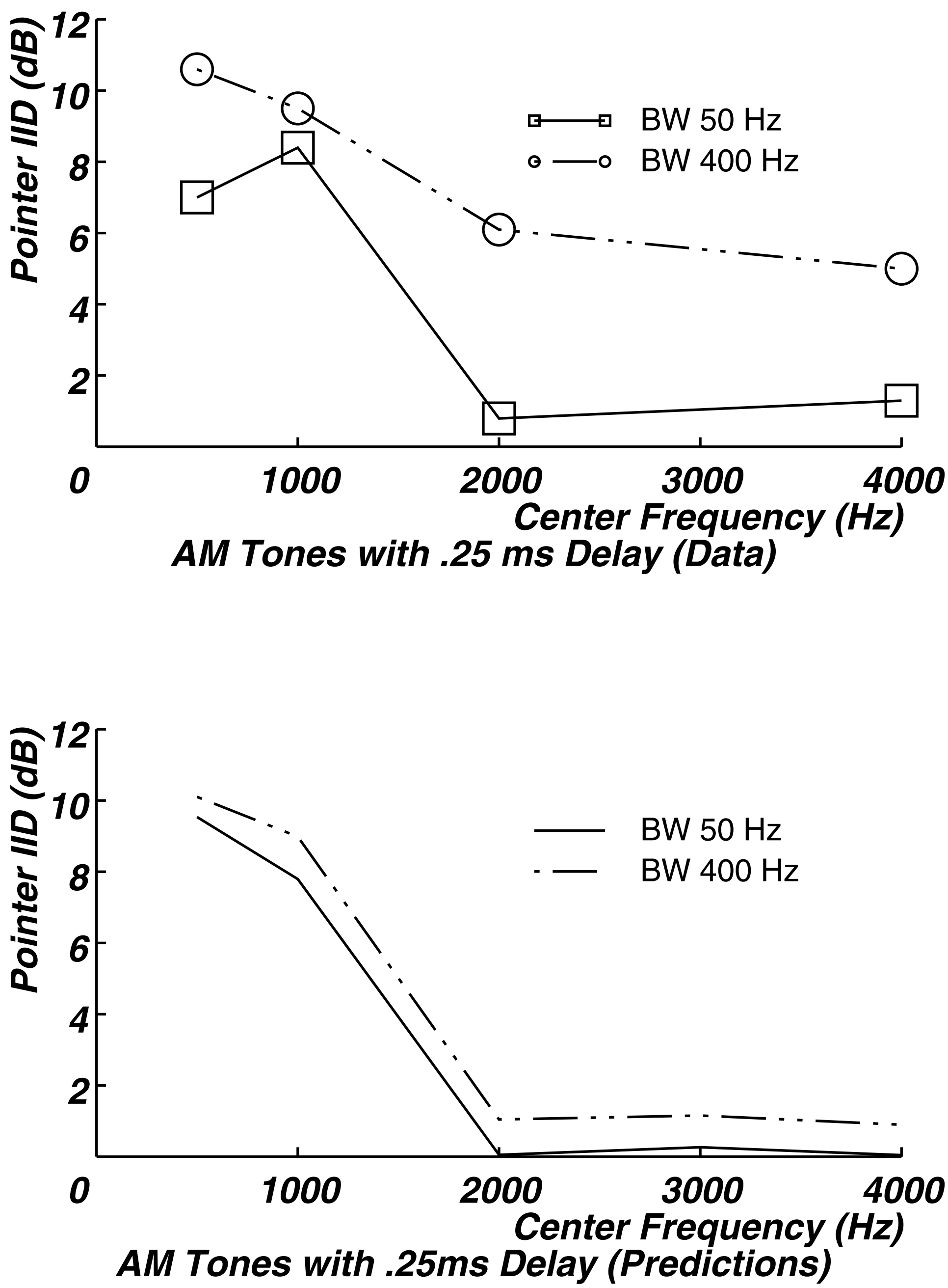
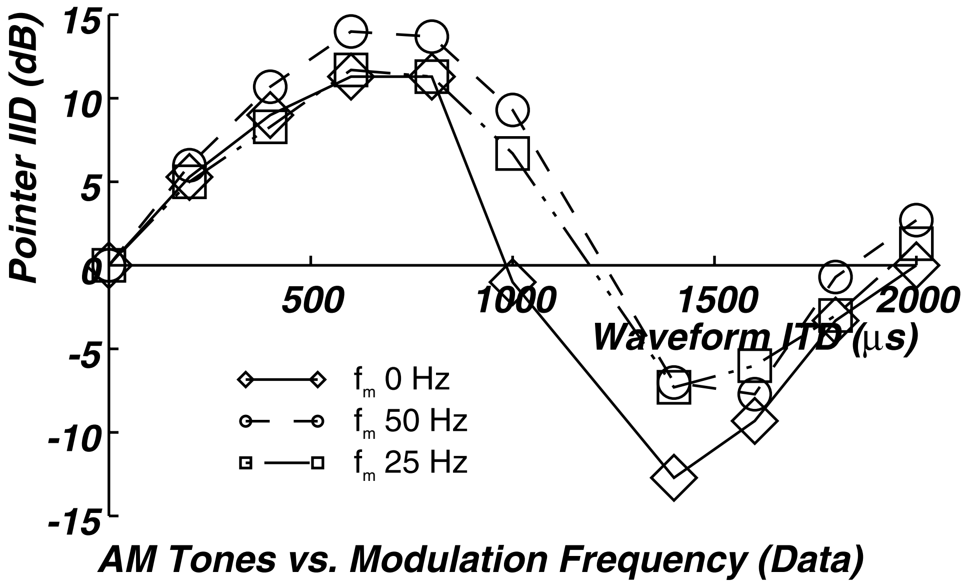


Figure 9. Comparison of data by Trahiotis and Bernstein (1986) and theoretical predictions describing the dependence of the perceived laterality of bandpass noise on center frequency and bandwidth.



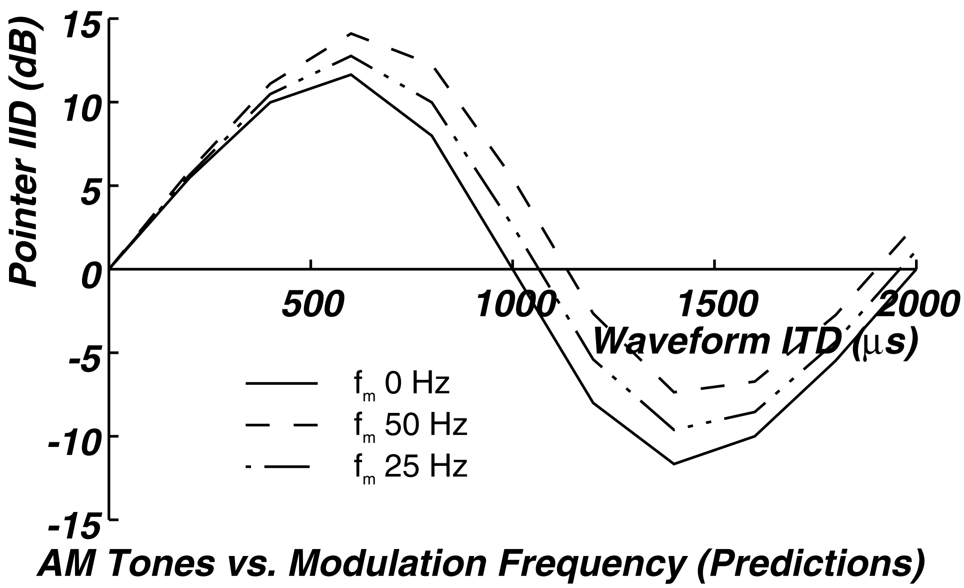


Figure 10. Comparison of data by Bernstein and Trahiotis (1985) and theoretical predictions describing the dependence of the perceived laterality of low-frequency amplitude-modulated tones on modulation frequency and waveform ITD delay.

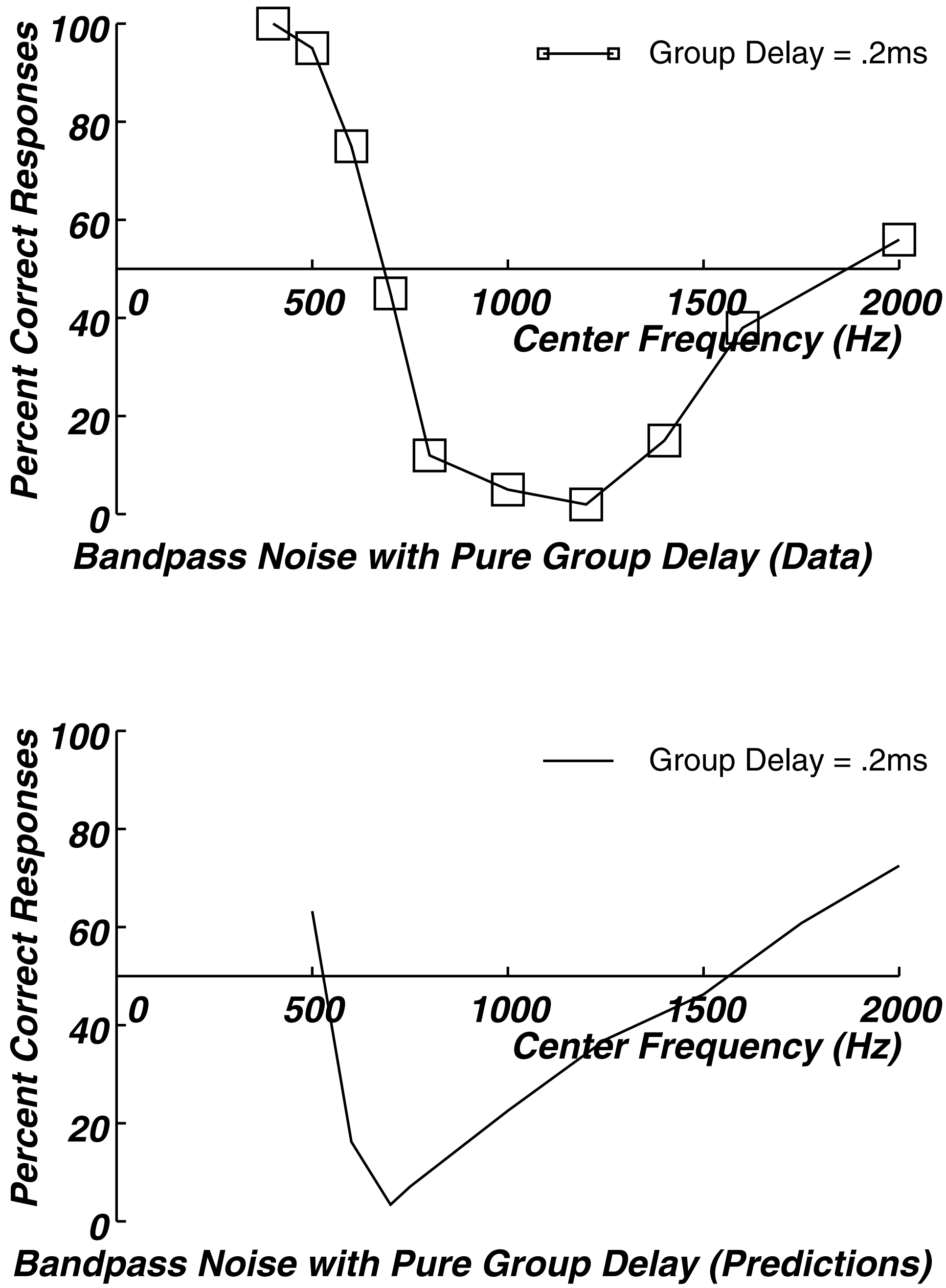


Figure 11. Comparison of data by Henning (1983) and theoretical predictions describing the dependence of the perceived laterality of bandpass transients presented with pure group delay. Data and predictions are plotted as a function of center frequency.

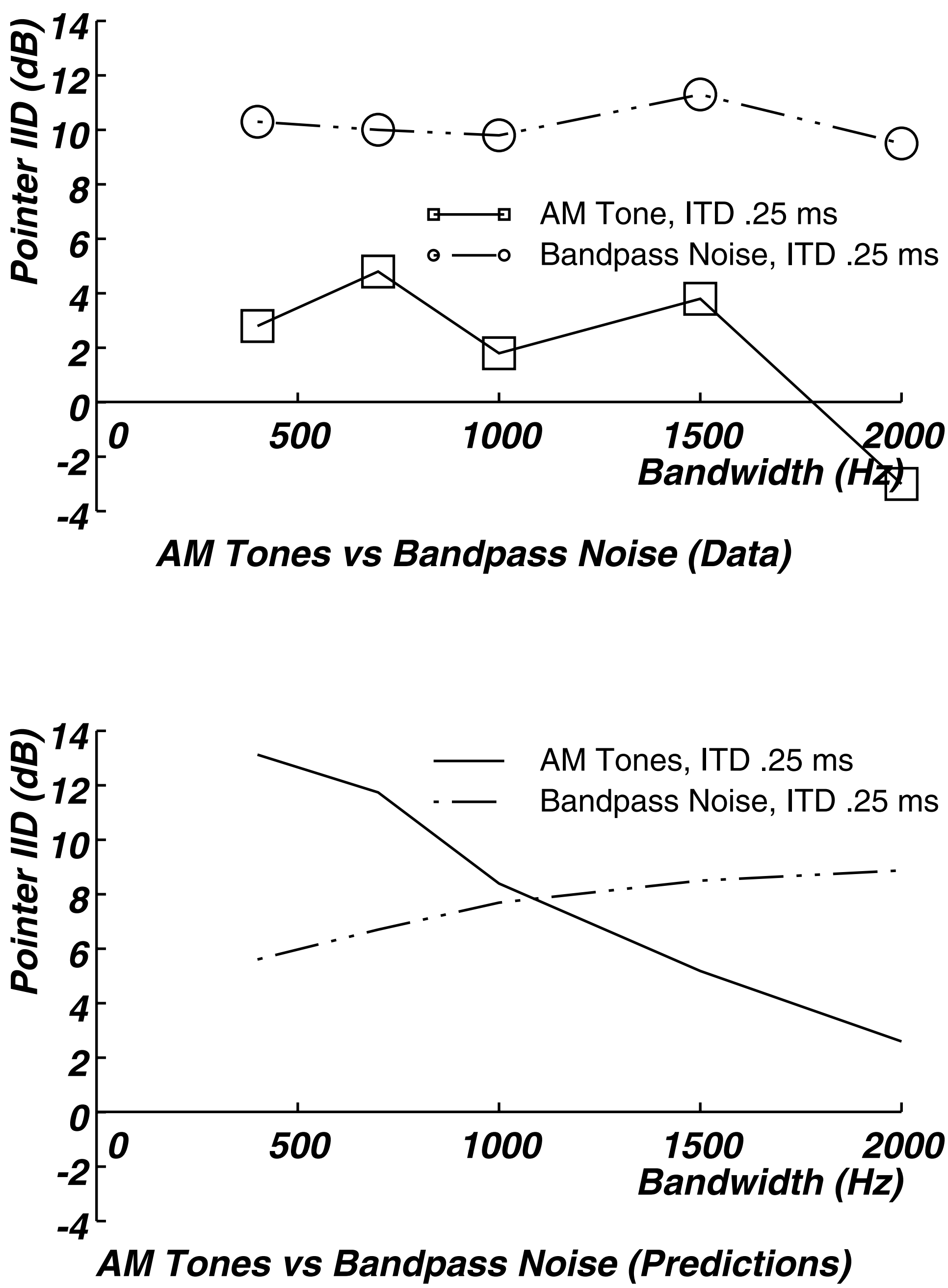


Figure 12. Comparison of data by Trahiotis and Bernstein (1986) and theoretical predictions comparing the laterality of bandpass noise and amplitude-modulated tones, as a function of bandwidth.

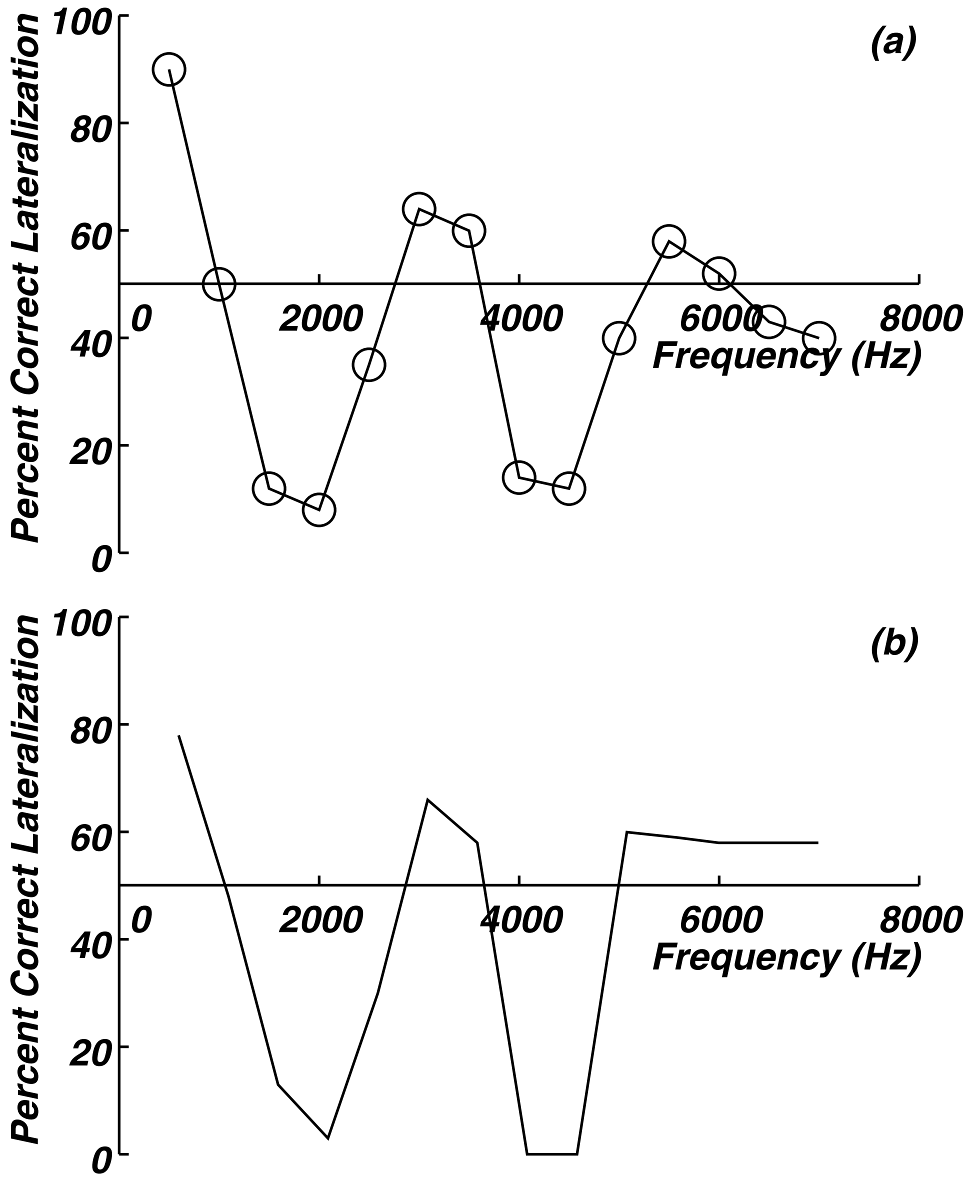
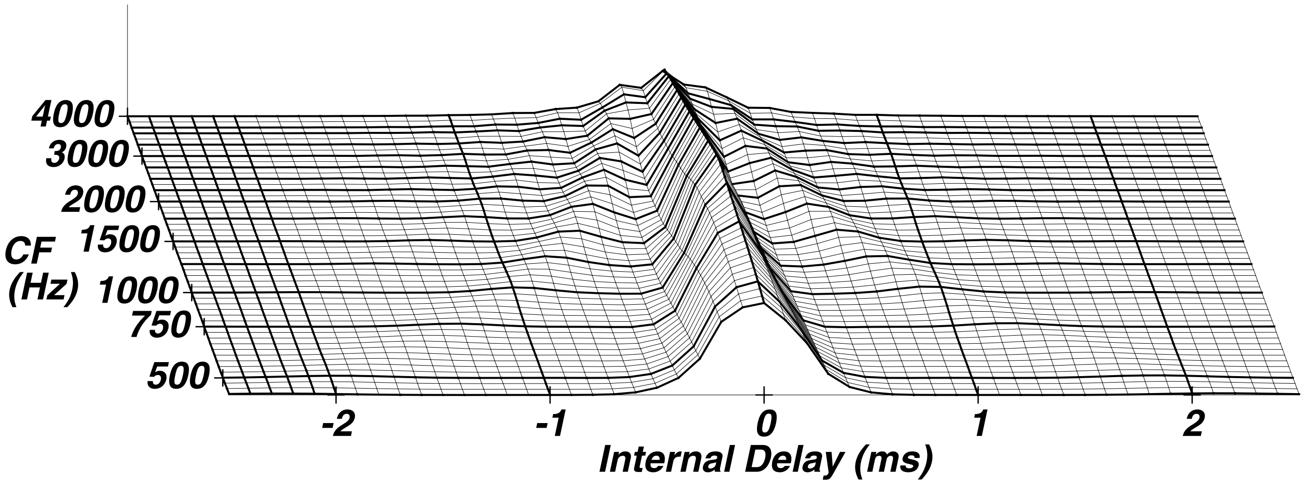
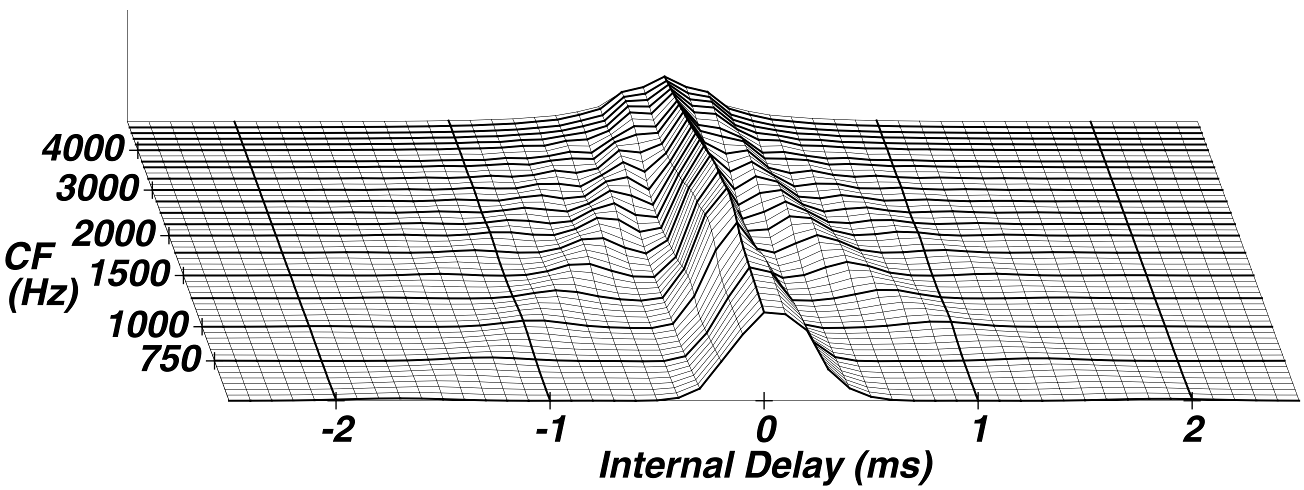


Figure 13. (a) Typical lateralization results by Hafter *et al.* (1989) for gated-noise stimuli with as a function of center frequency f_c. Lateralization percentages below 50 percent are the counterintuitive "illusory" reversals. (b) Predictions of the extended position-variable model for the same stimuli.



(a) Center Frequency 2000 Hz



(b) Center Frequency 3000 Hz

Figure 14. (a) Cross-correlation patterns showing the response of an ensemble of binaural fiber pairs to a gated-noise stimulus with T_D equal to 400 µs and f_c equal to 2000 Hz [panel (a)] and 3000 Hz [panel (b)]. The horizontal axis indicates the internal interaural delay of the fiber pairs (in ms), and the oblique axis indicates the characteristic frequency of the auditory-nerve fibers (in Hz).