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The Effects of the Interaural Parameters of the Background Noise on Dichotic Pitch Detection

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THE EFFECTS OF THE INTERAURAL PARAMETERS OF THE BACKGROUND NOISE ON DICHOTIC PITCH DETECTION

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VITA

The author, Anthony Nelson Grange, is the son of Robert Orville and Gwyndelen Cherry Grange. He was born October 1, 1964, in Hattiesburg, Mississippi.

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INTRODUCTION

In order to localize the source of a sound in the horizontal plane, the auditory system compares the waveforms arriving at the two ears to evaluate interaural time and level differences. Differences in interaural level are caused by the "sound shadow" that the listener's head creates when a sound source is off center; interaural differences of time are introduced when the distance between the sound source and one ear is not equal to the distance between the source and the other ear. Due to the physical qualities of the listening environment (e.g., head size, the speed of sound in air, and the wavelength-dependent reflective properties of sound), the most important localization cue for low frequencies (up to about 1500 Hz) is the interaural difference of time, or IDT.

Because impinging sounds often consist of many different frequencies, and because sounds are often arriving from different sources simultaneously, the auditory system must separate the waveform into individual frequency components to make meaningful interaural comparisons. This separation is in part accomplished by a peripheral frequency analysis with the cochlea serving as a set of bandpass filters for the incoming sound. The outputs of frequency-matched filters from the left and right ears can then be compared to determine the interaural parameter of each component.

The remaining problem for the auditory system is to recombine the information from different frequency regions in such a way that all of the components arising from one sound source are segregated from those arising from other sound sources. One way that the auditory system might do this is to group together those frequency components that have common interaural parameters. This would entail comparisons of interaural parameters across frequency regions, a cross-spectral integration of information.

One way to investigate the nature of the mechanism that assesses and compares interaural information across frequencies is to measure subjects' performance on tasks that require subjects to discriminate between different interaural parameters at a given frequency, while the interaural parameters of other frequency components are manipulated. In other words, over what range of frequencies will the processing of IDT's at one frequency be affected by those at other frequencies? Put this way, the question becomes somewhat analogous to that of auditory-filter bandwidth in the periphery.

A number of studies have been attempted to assess the range of frequencies over which interaural parameters can interact. Most of these can be grouped into two categories, defined by the binaural phenomenon under investigation: binaural unmasking, resulting in a masking level difference (MLD), and dichotic pitch.

The task in studies of the MLD is detection of a signal, which is embedded in noise of varying interaural configurations (see Green & Yost, 1975 for a review). The essential finding of these studies is that signal detection threshold is dependent on the relationship between the interaural configuration of the masking noise and the signal. As an example, when the signal is presented with an interaural phase shift of 180° and the noise is interaurally in phase (termed the N_oS_π condition), signal detection improves by about 15 dB when compared to thresholds obtained when both signal and masker are interaurally in phase (N_oS_o, see Green & Yost, 1975 for a review). As the name implies, the MLD is the difference between thresholds obtained when the interaural parameters differ between signal and masker, and the threshold for the condition in which both signal and masker are interaurally in phase.

Based on measurements of the MLD, it has been concluded that the bandwidth of the effective masking noise is wider in binaural conditions than in monaural conditions. An early attempt to measure the width of these "binaural critical bands" made use of the bandlimiting technique (see Fletcher, 1940). This method assumes that as the bandwidth of a masking noise centered around the signal frequency is decreased, signal thresholds will begin to drop once the noise is narrower than the auditory critical bandwidth; that is, only when decreasing the width of the masking noise removes non-signal (masker) energy from the filter. Bourbon and Jeffress (1965) and Sever and Small (1979) found that, for N_oS_o conditions, critical bandwidth estimates were consistent with monaural estimates. However, when either the signal or masker was presented 180° interaurally out of phase, the masker bandwidth at which thresholds began to decrease was somewhat greater than that of the diotic conditions. Based on this evidence, the conclusion was drawn that binaural critical bands were wider than monaural estimates.

Another class of experiments using the MLD is that in which the interaural parameters of the masking noise are frequency dependent. Sondhi and Guttmann (1966), for example, used noise in which the frequencies within an inner band centered around the target frequency were interaurally in phase, and the frequencies outside this band were 180° interaurally out of phase, or vice versa. They also used signals that were either interaurally in phase or 180° out of phase. By varying the width of the inner band in each of these four conditions, they were able to make estimations of the width of the noise that is effective in lowering the signal thresholds when the interaural parameters differ between signal and masker. In conditions where the interaural parameters differed between signal and masker, the width of the spectrum effective in masking was greater than in the conditions where the interaural parameters did not differ.

One interesting finding of this study was that the shapes of the functions showing the increases or decreases in MLD as a function of the width of the inner band differed, depending on the relation between the interaural configuration of the tone and the interaural configuration of the inner band of noise. When the inner band had the same interaural configuration as the signal (e.g., $S_oN_{\pi o\pi}$)[1], the MLD decreased rapidly as a function of the width of the inner band. However, in conditions where the inner noiseband and the signal were of differing interaural configurations (e.g., $S_oN_{o\pi o}$), the MLD increased only gradually as the width of the inner band increased.

Kohlrausch (1988) estimated auditory filter shapes using a design somewhat similar to that of Sondhi and Guttmann (1966). He used a masking noise that was interaurally in phase below 500 Hz, and 180° interaurally out of phase above 500 Hz. Signal thresholds were highly dependent on the signal frequency in the vicinity of the interaural phase transition of the noise. Using the MLD's between antiphasic and homophasic signals at many frequencies and the calculated cross-correlation of the noise at each of these frequencies, he estimated filter bandwidths consistent with those of Patterson (1976), who used notched-noise maskers. Kohlrausch's calculations did not support the existence of a wider binaural critical band, and he pointed out that detection in monaural and binaural experiments do not depend on the same features. Monaural signal thresholds depend on the level of the signal compared to the masker, whereas binaural signal thresholds depend on interaural parameters as well as level (the greater the difference between the interaural parameters of the signal and the masker, the more easily the signal is detected).

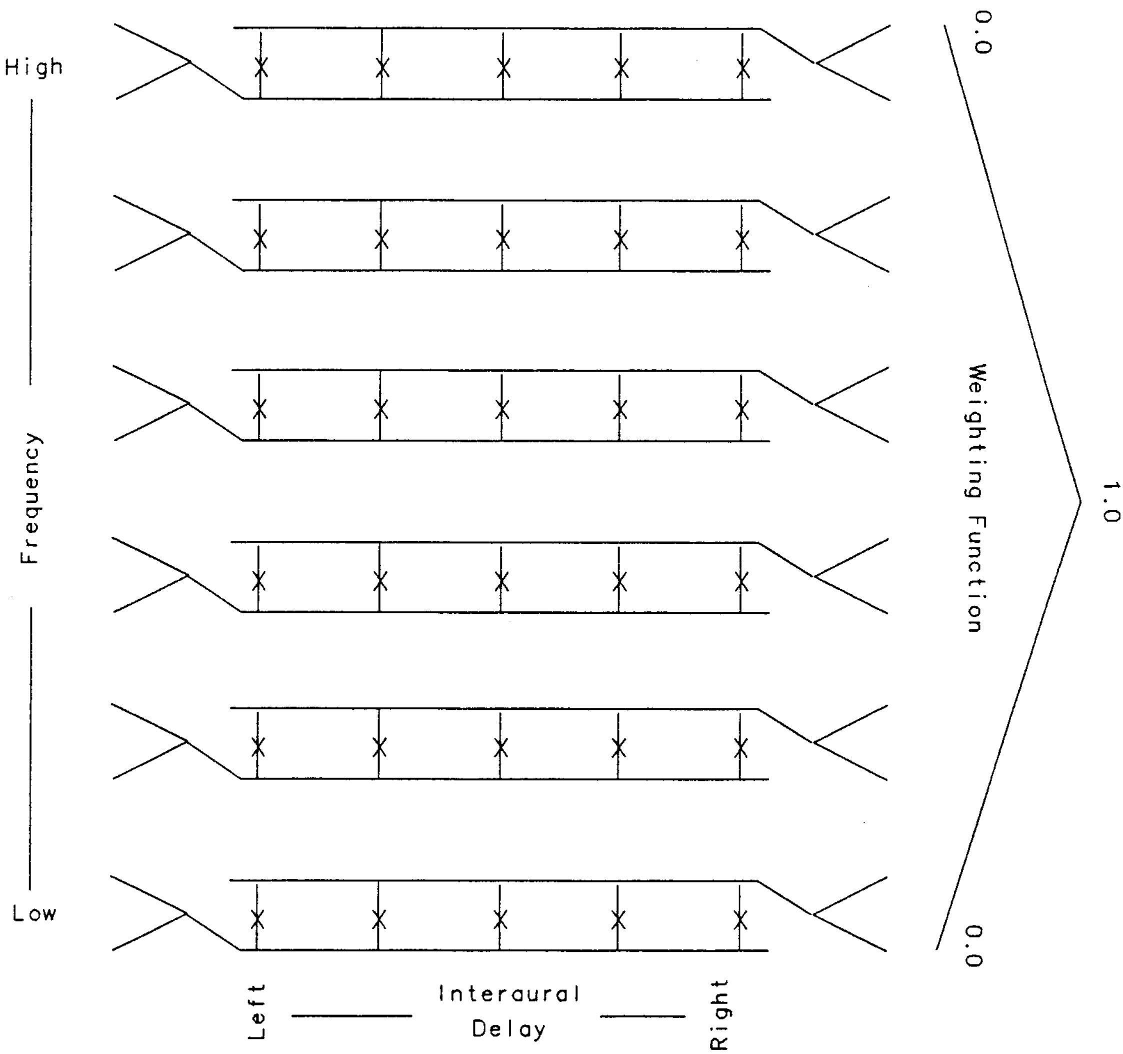
It was recognized early on that signal detection thresholds were affected when the correlation of the masking noises at the two ears changed. It is clear, however, as Robinson and Jeffress (1963) point out, that it is not simply decorrelation that is responsible for the shift in thresholds; results will also differ with the method used to decorrelate the two noises. Robinson and Jeffress (1963) lowered the correlation of the two noises by adding varying proportions of independent noise to the noise common to each ear, and finding thresholds for both S_o and S_π signals, masked by both N_o and N_π maskers. In contrast, Langford and Jeffress (1964) introduced an interaural delay to the noise to decorrelate it. The intracranial images that each of these manipulations evokes are quite different from each other. In the case where diotic noise has a proportion of independent noise added to each channel, the intracranial image remains centered; however, it becomes more and more diffuse as a smaller percentage of the noise is common to both ears. When decorrelation is introduced by an interaural delay of the noise, the intracranial image remains compact, but is lateralized to one side of the head (Robinson & Jeffress, 1963). Another consideration that may be relevant in the case of decorrelating by use of an interaural delay is that an assumed neural delay corresponding to the interaural delay would render the effective correlation approximately 1.0. In other words, delayed signals are still coherent (interaural correlation is 1.0, given some neural delay), whereas the Robinson & Jeffress technique does not produce coherent signals. Still another way to decorrelate the noise is by using frequency dependent interaural parameters, as did Kohlrausch (1988), where correlation differs with frequency.

Experiments using dichotic pitches are somewhat fewer in number. Dichotic pitches are created purely by binaural interaction within the auditory system. When identical wideband noises are presented to each ear over headphones, the subject simply hears the noise centered in intracranial space. If an interaural delay of a narrow section of the noise is introduced, however, most subjects will report hearing a pitch associated with the center frequency of the delayed band, provided that the CF is at a low frequency, between 200 and 1600 Hz (Cramer & Huggins, 1958). If one earphone is removed, the pitch perception disappears, since each signal consists only of wideband noise with random phases for each component. Yost (1991a) estimated thresholds for detecting an interaural phase delay in a narrow section of a wideband noise (dichotic pitch). He found that thresholds were lowest when the center frequency of the delayed band was approximately 500 Hz, and when the width of the band was approximately 100 Hz. In a more elaborate investigation, Yost (1991b) measured threshold frequency discrimination of two dichotic pitches. He found that pitch discrimination was best for bandwidths between 8 and 32 Hz, when the center frequencies of the delayed bands were between 400 and 500 Hz. Thresholds were similar to monaural values found for narrow bands of noise judged to have the same pitch strength and saliency as the dichotic pitches suggesting that dichotic pitches may have characteristics similar to narrow bands of noise.

As Kohlrausch (1988) pointed out, different factors can influence monaural versus binaural signal detection. For monaural signal detection, the frequency content and level of the masker are crucial in determination of detection threshold. The use of dichotic pitch stimuli eliminates the possibility that frequency content and level of the noise are affecting the amount of masking, since these parameters do not differ between the two ears or between intervals. The results will therefore allow for determination of binaural filter bandwidth not established at the level of the periphery.

The present experiments will be interpreted in terms of a simple model making assumptions common to many current models of binaural processing (Raatgever and Bilsen, 1986; Colburn, 1977). Figure 1 shows a diagram of the basic elements of this model. Emphasis will be placed on three distinct components: filters, cross-correlators, and a weighting function. The incoming auditory waveform first passes through a bank of bandpass filters, located in the periphery of the system. Outputs of frequency-matched left and right filters (spike trains) project to coincidence detectors, which fire if spikes from both peripheral filters reach the coincidence detector nearly simultaneously. It is assumed that many fiber bundles are associated with each peripheral filter, but that

Figure 1. Schematic of the model of binaural hearing used in the current experiments. Peripheral auditory filters are distributed along the frequency axis. One fiber from each of a pair of frequency-matched filters project to a single coincidence detector, which will fire if spikes from both filters arrive simultaneously. Coincidence detectors are labelled as X. To simplify the figure, all of the coincidence detectors are shown as receiving input from a single line which serves as a delay line for all. The weighting function is shown as triangular. The weights 1.0 and 0.0 refer to the range of relative weight that the interaural parameters at different frequencies contribute when the information is combined. The coincidence detectors are distributed along the axis of interaural delay.


High
Frequency
Low
Left
Interaural
Delay
Right
Weighting Function
0.0
1.0
0.0

only one fiber bundle from each ear projects to any given coincidence detector. Therefore, many coincidence detectors are associated with each set of matched filters. For each coincidence detector, a delay line introduces a delay in the spike train from one of the filters, so that each detector will fire maximally to a specific interaural delay in the auditory signal. The pattern of firing along the array of coincidence detectors at a given frequency represents the cross-correlation function of the outputs of the two filters at that frequency.

The third component of this model is the weighting function. If information is combined across frequency channels, so that the outputs of the coincidence detectors from all frequencies that correspond to a particular interaural delay are combined, it may be the case that the information from more distant frequencies is weighted less than the information from closer frequencies. The shape of the weighting function is assumed to be fundamental in determining the extent to which interaural parameters at one frequency can interfere with the processing of interaural parameters at another frequency. It is assumed that there is a weighting function associated with, and centered on, each set of peripheral filters, so that the spectral region containing the signal is always weighted most heavily. The weighting functions proposed in this model should not be confused with the weighting function of Raatgever and Bilson (1986), which suggests that the frequency region around 600 Hz plays a dominant role in binaural processing.

The term "binaural critical bandwidth" has not been used in this model since critical bands have previously been descriptions of the frequency range over which noise can mask the detection of an energy increment caused by the addition of a signal. However, it is likely that detection in binaural tasks is determined by something other than, or in addition to, energy detection. If "binaural critical bandwidth" is taken to mean the range of frequencies over which information is combined, then the relevant data must be explained by one, or a combination of several, of the components of the binaural model. However, estimates of the binaural critical band vary greatly with the stimulus employed. Cokely and Hall (1991) suggested binaural processing bands of 1000 Hz for signals centered on 500 Hz, based on a modified bandlimiting technique. Binaural critical bandwidth seems better applied as a description of a class of phenomena than as a mechanism of hearing.

If information about interaural cues is combined across frequency channels, and the frequency range over which this combination occurs is wider than the auditory filter bandwidth at a target frequency, then subjects thresholds for detecting narrowband phase shifts at the target frequency should be affected by manipulation of the interaural configuration of frequencies outside of the auditory filter, but inside of the bounds of the spectral weighting function. The purpose of the following set of experiments is to investigate this possibility.

EXPERIMENT I

Thresholds were obtained for detection of an interaural phase shift of a narrow portion of a wideband noise, with a distractor phase shift present in a different spectral region. The target band of noise was centered at 500 Hz, with a bandwidth of 4% of the CF (20 Hz). The delay of the target band was always in the left signal, so that the dichotic pitch was localized on the right side of the head. Performance was measured with the distractor noise band located at 6 different center frequencies: 350, 400, 450, 550, 600, and 650 Hz. The width of the distractor band was also 4% of the CF so that both the target and distractor bandwidth would comprise similar proportions of the peripheral filter centered on that particular frequency, assuming that the widths of the peripheral filters are a constant percentage of center frequency. The differences in distractor bandwidth, ranging from 14 Hz to 26 Hz, were not expected to have a strong influence on performance, and several conditions were repeated with a constant distractor bandwidth of 20 Hz to test this assumption.

Masking of the target dichotic pitch by the distractor pitch could be caused by several factors. The perceived loudness, or strength, of a dichotic pitch should be greater as the interaural delay is increased (reaching a maximum when the narrow band is 180° interaurally out of phase with the background noise). If the strength of the distractor pitch determines the degree to which the target pitch is masked, then maximum masking should occur when the distractor band is 180° interaurally out-of-phase.

It is also possible that the lateralized position of the distractor pitch relative to the target position is an important factor in the determining the amount of masking. If information across frequencies is combined by some kind of summation of the activity at coincidence detectors along trajectories perpendicular to the delay axis, then maximum masking might be expected to occur when the interaural delay of the distractor band is equal to that of the target band. Trajectories perpendicular to the delay axis would traverse those coincidence detectors that correspond to the same interaural delay at all frequencies. If the distractor interaural delay causes activity at a coincidence detector that lies along the same trajectory as the activity at the coincidence detector at the target frequency, then this may cause increased interference.

Conditions were run in this experiment with a distractor band interaural delay of 90°, and also with the distractor delay equal to that of the target band. Large differences in the pattern of masking between the two sets of conditions should indicate which characteristic of the distractor pitch is predominantly responsible for the masking. However, with pitch strength dependent on location, the masking effects of each distractor characteristic can not be completely separated.

METHODS I

A modified two-interval forced-choice task was used in which the subject had to identify which of two intervals contained the interaural delay of the target band. The distractor delay was present in both intervals. The intervals were 500 ms in duration with 10-ms $\cos^2$ rise/fall ramps, and were presented with no temporal separation. Further, forward and backward fringes were added, which were identical to a nonsignal interval. The distractor interaural delay was present in the fringes, and both fringes were ramped on and off in the same manner as the test intervals. The fringes were presented immediately before and after the two test intervals, with no separation. Therefore, an entire trial consisted of 2000 ms of noise. The distractor delay was always present, and the target delay would be introduced during the second or third 500-ms section.

Several issues warranted consideration in justifying these task modifications, which were made for economy of time. First, in a two-interval task, the intervals should be identical except for the presence of the target in one of them. In this experiment, however, if the target delay was in the first interval, then the actual forward fringe was 500 ms and the actual backward fringe was 1000 ms. The fringe durations were reversed if the second interval contained the target delay. Based on the observations of Yost (1985) that fringe durations of 500 ms are effectively continuous, it was reasoned that the inequality of the intervals (fringe length) would not be problematic.

The second issue that arose was that no visual cue was given to signal the onset and offset of each interval. The subjects reported that the short "gaps" caused by the offset and onset ramps between each 500-ms section of noise were sufficient to delineate the different intervals, so that incorrect responses were not due to temporal confusion. To test this more objectively, on each of the trials, there was a 25% chance that the target band would contain an interaural delay of 90°, which subjects could detect easily in all conditions (with the exception of one subject in one condition). If the subjects responded less than 95% correctly on these trials, the block was not included in threshold estimation. These trials also served to occasionally "remind" the subjects of the frequency of the target dichotic pitch.

Data were collected in blocks of 100 trials, which were broken up into two 50-trial sets. Before each 50-trial set, subjects were allowed to listen to as many practice trials as they wished. The subjects then initiated a set of test trials by pushing a button on the response terminal. Daily sessions lasted two hours, in which approximately 500-600 trials were run.

Thresholds were estimated from 3-point psychometric functions, with each point based on at least 150 trials. Since approximately 25% of the trials in a block contained a 90° delay of the target band ("reminder" trials), two blocks yielded roughly 150 test trials. The best-fitting line through the three points was determined using a linear regression on linear coordinates, and the threshold interaural delay was defined as the delay corresponding to $d' = 1.00$.

Stimuli were presented to subjects seated in a sound-attenuating chamber over Telephonics (TDH-49) earphones suspended in Auraldomes. The noise was generated on a Masscomp minicomputer using a 4096-point inverse FFT. The noise spectrum was flat from 1 - 2048 Hz, with the level of each component at 52 dB SPL. Two 2000-ms bursts of noise (target and non-target) were generated for each condition. For each of the four sections making up a given trial, a randomly selected 500-ms section of the noise burst was used. Stimuli were played out by 16-bit digital-to-analog converters set to a rate of 4096 Hz per channel, lowpass filtered at 1500 Hz with a nominal slope of 48 dB / octave (Rockland Series 2000), and then attenuated (Tech Lab, Inc.). Crown stereo amplifiers were used to drive TDH 49 headphones.

The subjects in Experiment I were the author and two Loyola University students who were paid for their participation. All three had at least 8 hrs of training before data were collected.

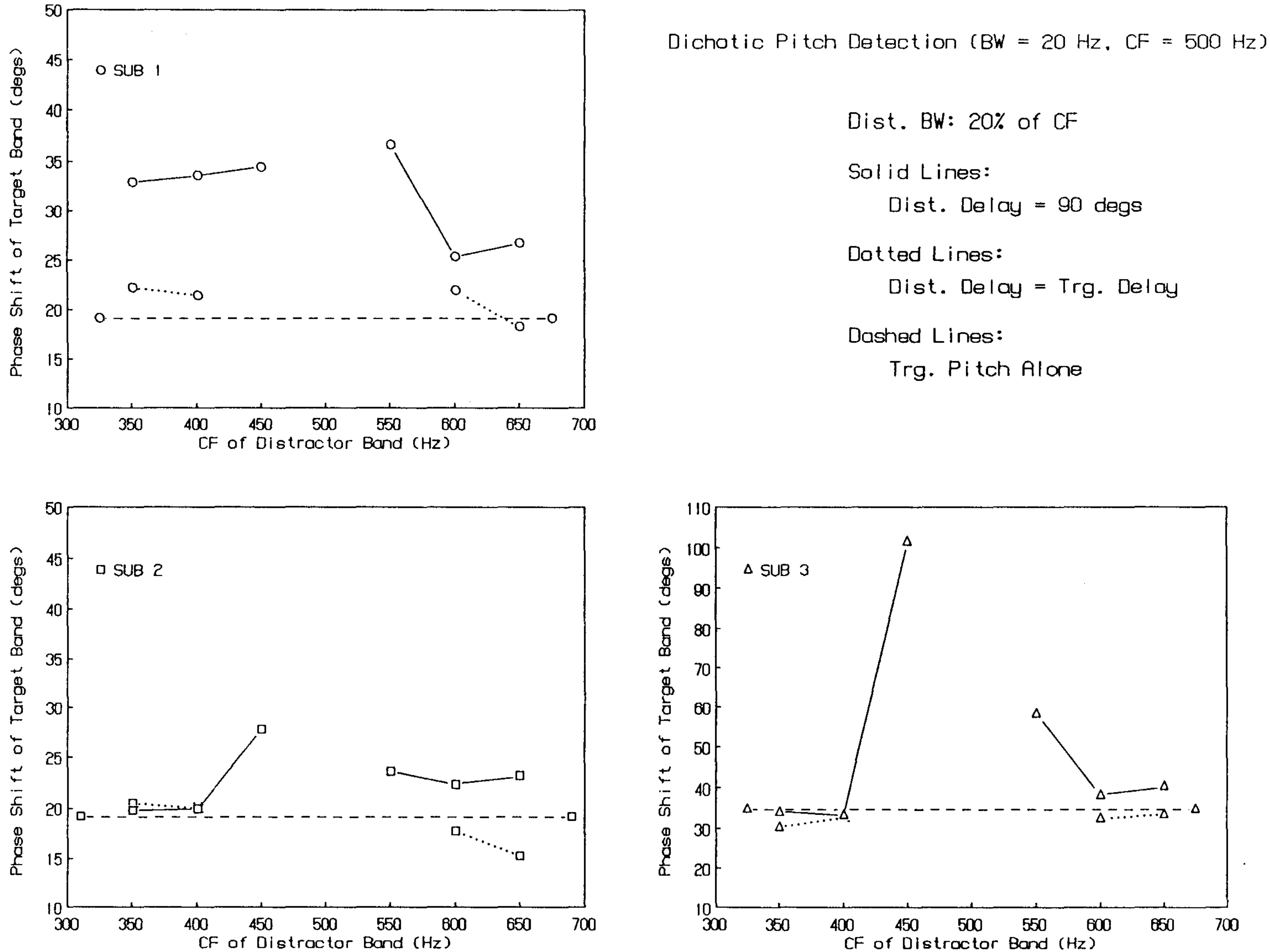
RESULTS I

The results of Experiment I are shown in Figure 2. Each panel represents the data from one subject. Threshold interaural phase delays of the target are plotted as a function of the center frequency of the distractor band. The solid lines represent conditions in which the distractor delay was always 90° to the left, the dotted lines represent conditions in which the distractor delay was equal to the target delay. The dashed horizontal lines represent each subject's threshold for the target dichotic pitch in the absence of a distractor pitch. Note that the range of values on the Y axis is larger for subject 3, compressing the data in that panel relative to the other two.

In general, the target pitch was masked more effectively by a distractor pitch with an interaural delay of 90° than a distractor pitch with an interaural delay equal to that of the target. For subject 1, in the 400-Hz condition, the shift in threshold interaural delay was almost 15°, and at no distractor pitch CF was the threshold for an equal-delay distractor condition substantially higher than the corresponding 90° delay condition. This provides some support for the idea that a stronger, more salient distractor pitch, caused by a greater interaural delay at the distractor CF, is more disruptive of the processing of the interaural parameters at the target frequency than a weaker distractor pitch, even though the target and distractor delays are equal.

Though there were some fairly large individual differences, it does

Figure 2. Threshold interaural delays for dichotic pitch detection in the presence of a second (distractor) dichotic pitch are plotted as a function of the center frequency of the distractor pitch. Each panel shows the data for a different subject. The solid lines represent conditions in which the distractor delay was 90°, and the dotted lines represent conditions in which the distractor delay was equal to that of the target. The horizontal dashed lines indicate each subjects' threshold for the target dichotic pitch alone.


Dichotic Pitch Detection (BW = 20 Hz, CF = 500 Hz)
Dist. BW: 20% of CF
Solid Lines:
Dist. Delay = 90 degs
Dotted Lines:
Dist. Delay = Trg. Delay
Dashed Lines:
Trg. Pitch Alone
SUB 1
SUB 2
SUB 3
Phase Shift of Target Band (degs)
CF of Distractor Band (Hz)
10
15
20
25
30
35
40
45
50
60
70
80
90
100
110
300
350
400
450
500
550
600
650
700

appear that when thresholds differed between distractor CF's for a given subject, performance was worse when the dichotic distractor band was closer to the target band. That is, thresholds were never substantially higher for conditions in which the dichotic distractor was further away from the target CF than when the distractor band was closer.

DISCUSSION I

The general result that thresholds increase as the CF of the distractor pitch is brought closer and closer to the target pitch suggests that some type of frequency selectivity exists, in which information about interaural parameters is combined across individual filter channels.

There were a number of individual differences reflected in the data. Several factors could account for the lack of consistency across subjects in Experiment I.

First is the possibility that the distractor dichotic pitches may have caused some attentional distraction, apart from the effects of the distractor band interaural delay on the summated cross-correlation function. If the second pitch resulted only in attentional distraction, then we would expect thresholds to be increased equally for all conditions, assuming that the pitch strength associated with a 90° interaural delay is equivalent for the distractor CF's used. If there were no attentional distraction, and only true spectral interference, then we would expect thresholds to increase as the CF of the distractor pitch was located closer to the CF of the target. It is possible that both of these factors influenced performance in this task.

Second is the nature of the task in conditions where the distractor CF is relatively close to that of the target. When the two pitches are farthest apart (the 350- and 650-Hz conditions), subjects reported that they did indeed perceive two separate pitches. In these conditions, the task was to detect the interval that contained two pitches. As the distractor CF was moved closer to the target, however, the task may change. Figure 3 shows the interaural phase configurations of two conditions. Configuration 3a is that of the 350-Hz condition, and configuration 3b, which was not used in the experiment, shows the two narrowband delays as close as they could be presented. This stimulus would produce a single dichotic pitch with a frequency of around 490 Hz. The subjects' task, in this case, would be to detect the difference between a 20-Hz wide dichotic pitch centered on 480 Hz and a 40-Hz wide dichotic pitch centered on 490 Hz. Yost (1991b) has measured frequency discriminability for dichotic pitches. He found that with 16-Hz wide interaural delays of 90°, thresholds for detecting a change in CF were about 35 Hz at center frequencies of 500 Hz. It is difficult to say at what frequency separation two different interaural delays presented together begin "fusing" into one dichotic pitch, but we cannot rule out the possibility that changes in the task affected each subjects performance differently.

The finding that thresholds only increased consistently in the 100-Hz condition makes it difficult to attribute the interference to only one of the components in our model. It may be the case that the interference arises because as the distractor delay is placed closer to the target pitch, the activity at that coincidence detector receives more weight as information is combined. However, the auditory system may instead be detecting a decorrelation between the outputs of a single pair of frequency-matched filters caused by the target narrow-band interaural delay. When the distractor band is far removed from the filter band, then

Figure 3. Interaural phase configurations for two conditions are shown. Panel 2a shows the 350-Hz condition, with a distractor pitch delay of 90°, and a target pitch delay of 45°. Panel 2b shows the interaural phases if the distractor pitch was placed adjacent to the target.

Fig. 2a

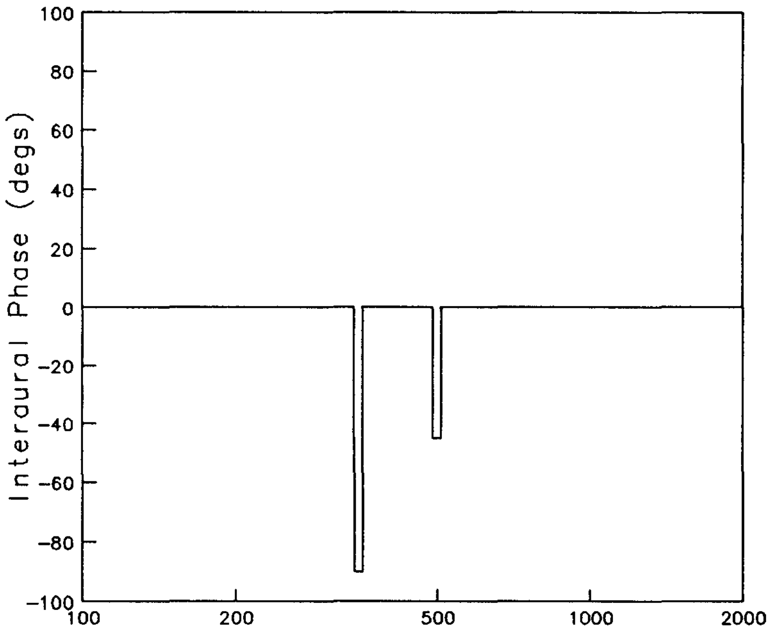
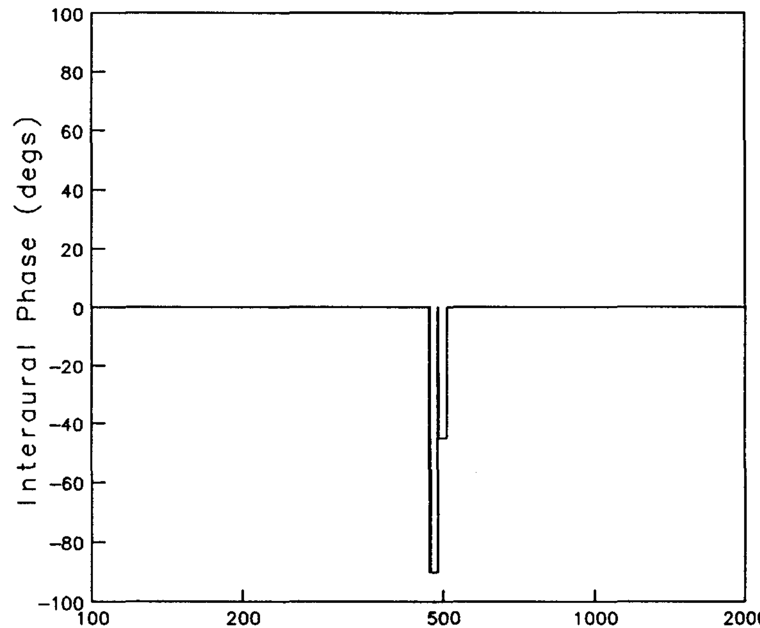


Fig. 2b



Frequency (Hz)

the task is to detect a decorrelation from a reference of 1.0. Previous studies have shown that thresholds for decorrelation detection are greater for a reference correlation of less than 1.0 than they are for a reference correlation of 1.0 (Gabriel & Colburn, 1981). If the distractor interaural delay causes a slight decorrelation in the output waveforms of the filters centered on the target frequency, then we would expect thresholds for detection of the target delay to increase.

The next experiment will use a different method of manipulating interaural parameters of off-target frequencies, which will eliminate possible problems associated with the use of two dichotic pitches.

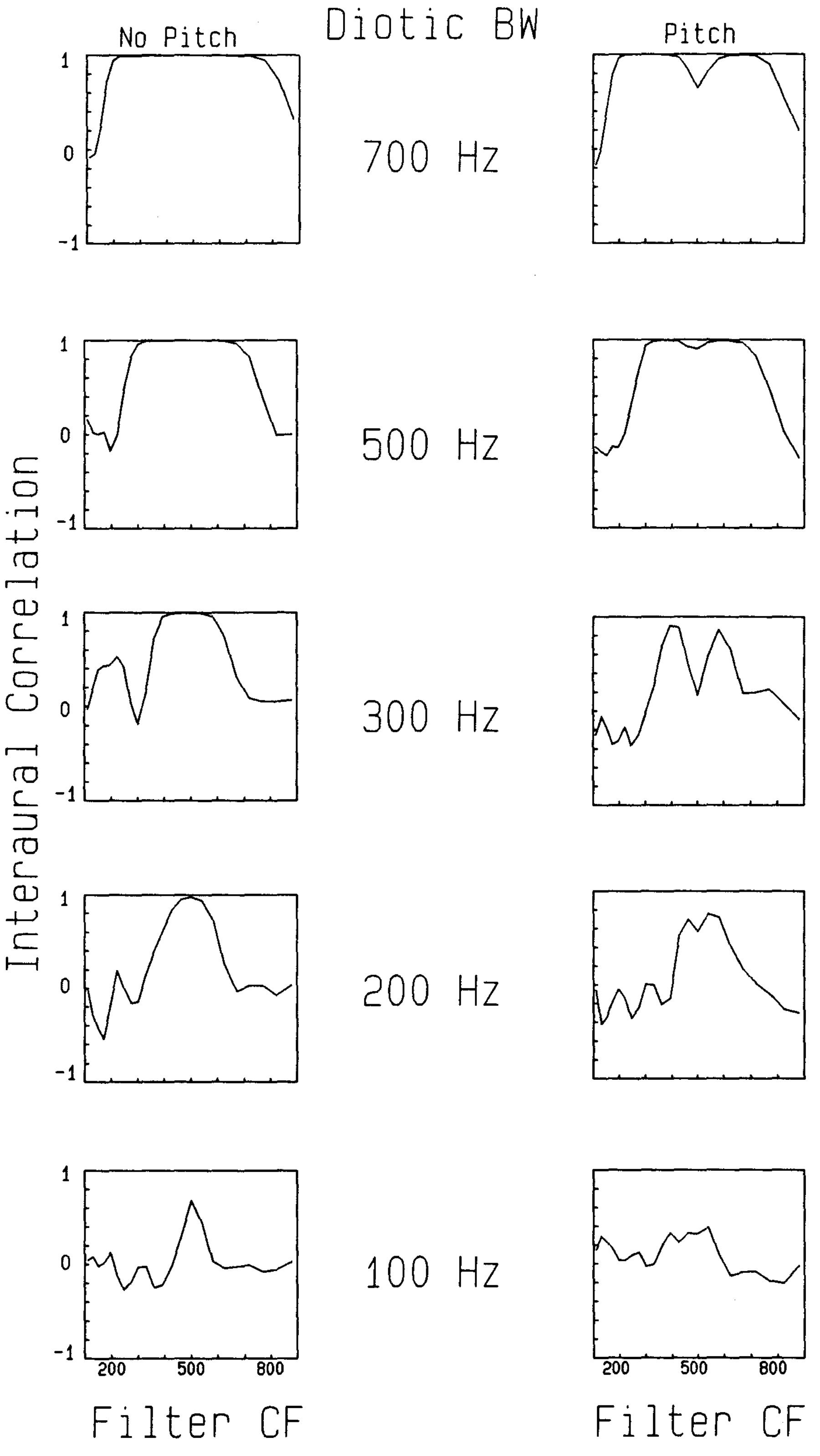
EXPERIMENT II

This experiment investigated the role of the diotic wideband noise as a background from which an interaurally delayed narrow band is discriminated. In order to perceive a dichotic pitch, the binaural system must be able to recognize the target band as "different" from the rest of the wideband noise, due to its phase shift. This suggests that the more well-defined and less variable the interaural parameters of the background noise, the easier the segregation of the background and the target band is.

The motivation for this experiment comes from the idea that information about the interaural parameters of each frequency channel may be combined across frequencies according to some weighting function. A triangular function would suggest that the interaural parameters of channels closest to the target frequency would be weighed most heavily, and as spectral distance from the target increased, frequency channels would have less and less influence on the combined pattern of activity.

The pattern of activity in a bank of cross-correlators with diotic noise as its inputs will exhibit a straight trajectory of peaks along the center of the frequency axis. This occurs since, in each array of coincidence detectors receiving input from a given pair of matched filters, the coincidence detector that is associated with a 0° interaural delay will be activated maximally. The top left graph in Figure 4 shows the interaural correlation coefficients across frequencies, which would

Figure 4. Each graph shows the assumed activation pattern of the coincidence detectors along a trajectory perpendicular to the delay axis at an interaural delay of 0°. The column of graphs on the left shows noise with no interaural delay within the diotic band, and randomized interaural phases outside of the diotic band. The right column shows noise of the same interaural configuration, with a 20-Hz wide 180° interaural delay centered on 500 Hz.


Diotic BW
No Pitch
Pitch
700 Hz
500 Hz
300 Hz
200 Hz
100 Hz
Interaural Correlation
1
0
-1
200
500
800
Filter CF
Filter CF

reflect the activity of the coincidence detectors associated with no interaural phase differences.

If activity from different frequency regions is summated along trajectories parallel to the frequency axis, so that each trajectory combines information about a particular interaural delay, then the summated pattern of activity for diotic noise will also have a large, well-defined peak at a delay of 0°. The summated pattern of activity across frequency channels is suggested as the basis of lateralization in several current models (Shackleton, Meddis, and Hewitt, 1992; Stern, Zeilberg, and Trahoitis, 1988). These models of lateralization are similar to the model of binaural hearing used in the current experiments. That the diotic noise may serve as a background for the diotic pitch refers to the idea that detection of an interaurally delayed narrow band of noise depends on the differences between the shape of the cross-correlation function at the CF of the narrow band and the summated pattern of activity over the rest of the spectrum.

One way of thinking of this is to assume that the auditory system groups all of the diotic noise components together and treats them as a single "object," since, based on interaural time differences, they would have most likely all been generated by the same sound source, (i.e., in the front). This "object" may be considered well-defined since there is no conflicting information over a large range of frequencies. When a narrowband interaural delay is introduced, there is a corresponding change in the cross-correlation functions of filter channels close to the center frequency of the narrow band. On the basis of these changes, the auditory system groups the frequencies within the narrow delayed band as separate from the rest of the diotic noise. The idea is that the more well-defined and less variable the diotic noiseband is, the easier it may be to distinguish the differences caused by the narrow band delay.

Several things need to be considered with regard to this hypothesis. One is the weighting function of the summation process, which would determine how much the cross-correlation function at a particular frequency contributed to the summated pattern of activity relative to the functions at other frequencies.

Also of relevance are the effects of IDP's at frequencies distant from the target band. Depending on the weighting function, if the cross-correlation functions of non-target frequencies had peaks at locations other than 0°, or had no prominent peaks, their effect on the summated pattern of activity may be to make its peak less well defined. If this were the case, a greater target interaural delay may be required to distinguish it from the predominant background noise.

This experiment looked at the effects of randomizing interaural phases of frequency components that were spectrally distant from the center frequency of a target-band interaural delay (dichotic pitch). The target band was centered within a wider band of diotic noise, which was varied in bandwidth. Interaural phases of components outside of this band were randomized (i.e., interaurally uncorrelated). Thresholds were measured in 8 different conditions, labelled by the bandwidth of the diotic noise: 900, 700, 500, 300, 200, 150, 125, and 100 Hz. In conditions where the diotic band is narrower, then, a larger proportion of the noise spectrum presented to the two ears is incoherent. Figure 4 shows cross-correlation coefficients plotted as a function as the center frequency of the filter they are based on. Noise samples from five of the experimental conditions are shown here, both without the target interaural delay and with a 180° target delay. Generally, as the diotic band is narrowed, more variability is introduced in the functions across frequency. Since portions of the noise are interaurally randomized, the actual pattern of activity across coincidence detectors at the midline will vary from trial to trial. Generally, however, as the width of the diotic band is narrowed, differences due to the interaurally delayed narrow band become less discernable.

A second set of conditions was run in which, instead of randomizing interaural phases of components outside of the diotic band, energy at these frequencies was removed. If spectral integration were mediated by a weighting function somewhat triangular in shape and centered on the target CF, so that detection of the dichotic pitch was more affected by the interaural parameters of frequency components spectrally closer to it, then there should be no differences between the two conditions when the width of the diotic band is at least as wide as the limits of integration. As the width of the diotic background is decreased, differences in thresholds between comparable conditions in the two experiments should increase in accordance with the shape of the weighting function.

METHODS II

A two down, one up tracking procedure was used in this experiment. Each trial consisted of two intervals, one of which contained the target narrowband delay. Each interval was 500 ms in duration, with 5-ms $\cos^2$ rise/fall ramps, and the two intervals were separated by 250 ms of silence. In the signal interval, the narrowband delay was introduced halfway through, so that the first 250 ms served as a forward fringe.

The stimuli were generated using a 2048-point inverse FFT program on a Masscomp minicomputer. For the left signal, starting phases were drawn randomly from a rectangular distribution ranging from 0° to 360° for each frequency component. For the right signal, for frequencies above and below the diotic band (centered on 500 Hz, with bandwidth varying with condition), starting phases were again drawn at random. The effect of this was to randomize interaural phases in these regions of the spectrum. Within the diotic band, the same phase arguments were used for both left and right signal. To introduce the target-band delay, the appropriate phase increment was added to the arguments of the left signal. A new noise sample was generated after each trial.

Frequency components of the noise were equal in amplitude (52 dB SPL/Hz). Stimuli were sent out over 16-bit digital-to-analog converters at a rate of 4096 points per second through anti-aliasing filters (1500 Hz cutoff, 48 dB per octave) and variable attenuators (Tech Lab, Inc.), and were amplified by Crown stereo amplifiers. In conditions where the total noise bandwidth was narrowed, the amplitude arguments for the inverse FFT were generated to create a 48 dB / octave rolloff on both the low and high frequency side. This was done to decrease the likelihood of edge pitches being created by sharp spectral edges (Hartmann, 1984) interfering with detection of the dichotic pitch.

Subjects were seated in a sound attenuating chamber and listened to the stimuli over TDH-49 headphones suspended in Auraldome ear cushions. The subjects were three Loyola University students who had previous listening experience in similar experiments.

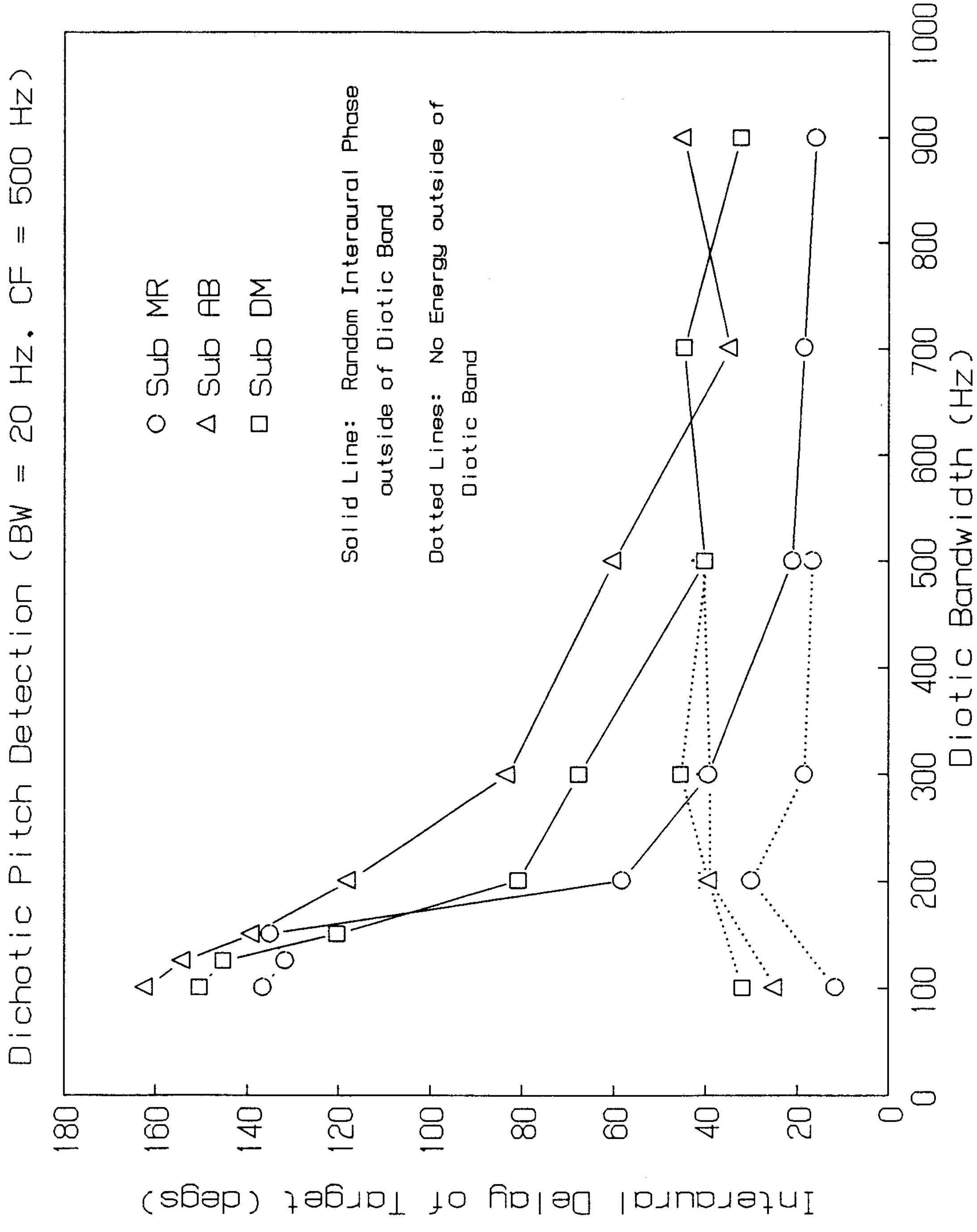
The data were collected in blocks of 50 trials. The step size was 9° for the first two reversals, and 3° for subsequent reversals. The first two reversals were disregarded, and thresholds were estimated by averaging the remaining even number of reversals (if an odd number of reversals occurred, the first three were disregarded). If there were fewer than 8 reversals in a block, then the block was discarded. Final thresholds were taken as the median of at least 6 blocks of 50 trials, generally obtained on at least 3 different days. Subjects usually ran 5-6 blocks during a daily session, and were presented with 2-3 different conditions in each session.

RESULTS II

The results for the three subjects in Experiment II are shown in Figure 5. Threshold interaural delays for dichotic pitch detection are plotted as a function of the width of the inner diotic band. Each symbol represents a different subject. The solid lines connect the conditions in which the noise outside the diotic band was uncorrelated $(N_{uou})^2$, and the dotted lines connect the conditions where the wideband diotic noise was simply narrowed (N_o).

The results indicate that thresholds increase dramatically as the bandwidth of the diotic noise is decreased from 500 Hz to 100 Hz, if interaural phases are randomized outside of this band. On the other hand, if the diotic band is made narrower by removing components outside of the band, thresholds decrease slightly, if they are affected at all. For subjects MR and DM, thresholds at a diotic bandwidth of 500 Hz were remarkably similar in both conditions, while for subject AB, the threshold for the random-phase condition was slightly higher. While the 700-and 900-Hz condition were not tested for the diotic band alone, it does not seem unreasonable to assume that thresholds for this subject would also converge at these bandwidths.

Figure 5. Threshold interaural delays for dichotic pitch detection are plotted as a function of the bandwidth of the surrounding diotic noise. Different symbols are used for the three subjects. The solid lines represent conditions in which the interaural phases of the noise outside the diotic band were randomized. The dotted lines represent conditions in which the noise outside the diotic band was removed.


Dichotic Pitch Detection (BW = 20 Hz. CF = 500 Hz)
Interaural Delay of Target (degs)
Diotic Bandwidth (Hz)
0
20
40
60
80
100
120
140
160
180
0
100
200
300
400
500
600
700
800
900
1000
Sub MR
Sub AB
Sub DM
Solid Line: Random Interaural Phase outside of Diotic Band
Dotted Lines: No Energy outside of Diotic Band

DISCUSSION II

Differences in thresholds between the N_{uou} and N_o conditions when the diotic bandwidth is less than 500 Hz seem to indicate that information about interaural parameters is combined across these frequency channels to create a background for the dichotic pitch. This experiment is procedurally analogous to one using notched noise as a masker, in which a tonal signal is presented against a wideband noise masker, centered within spectral notches of different widths to determine filter width at the frequency of the signal (Patterson, 1976). In this experiment, the lowest thresholds are found when the entire noise band is effectively diotic (the 900-Hz condition). The analogous notched-noise condition would use an extremely wide notch, so that the noise was clearly not masking the target tone. As the bandwidth of the diotic noise is decreased and interaural phases outside of this band are randomized, thresholds increase. Performance reaches its maximum (180° target shift) for all three subjects at a diotic bandwidth of around 100 Hz (using notched-noise, thresholds can be obtained at any notch width).

It still could be argued that the task is one of decorrelation detection between the waveforms at the two ears, based on the output of a single frequency channel. Table 1 shows average interaural correlations of the output waveforms of the auditory filter[3] centered on 500-Hz, for most of the conditions used in Experiment II. The 900-Hz condition was not computed since performance was similar to that in the 700-Hz

Table 1. The top panel shows interaural correlations and standard deviations between waveforms passed through filters based on Patterson (1976). For each diotic bandwidth, an average correlation of 7 waveforms was computed when there was no dichotic pitch, and when a dichotic pitch was present. The delay of the dichotic pitch corresponds to the mean of the threshold values from three subjects in that condition. The bottom panel shows correlations for the conditions in which the noise outside of the diotic band was removed. The correlations for the diotic (no narrowband delay) waveforms for the 300- and 200-Hz conditions are assumed to be equivalent to those of the 500- and 100-Hz condition.

Outer Phases Randomized

BW	TRG. DELAY	CORR.	STD.DEV
700	None	.9988	.0013
	Thresh.	.9485	.0190
500	None	.9987	.0013
	Thresh.	.9308	.0208
300	None	.9959	.0017
	Thresh.	.8618	.0544
200	None	.9758	.0078
	Thresh.	.7106	.0821
150	None	.9267	.0329
	Thresh.	.5127	.2011
125	None	.9005	.0436
	Thresh.	.3582	.2491
100	None	.8462	.0227
	Thresh	.4024	.1761

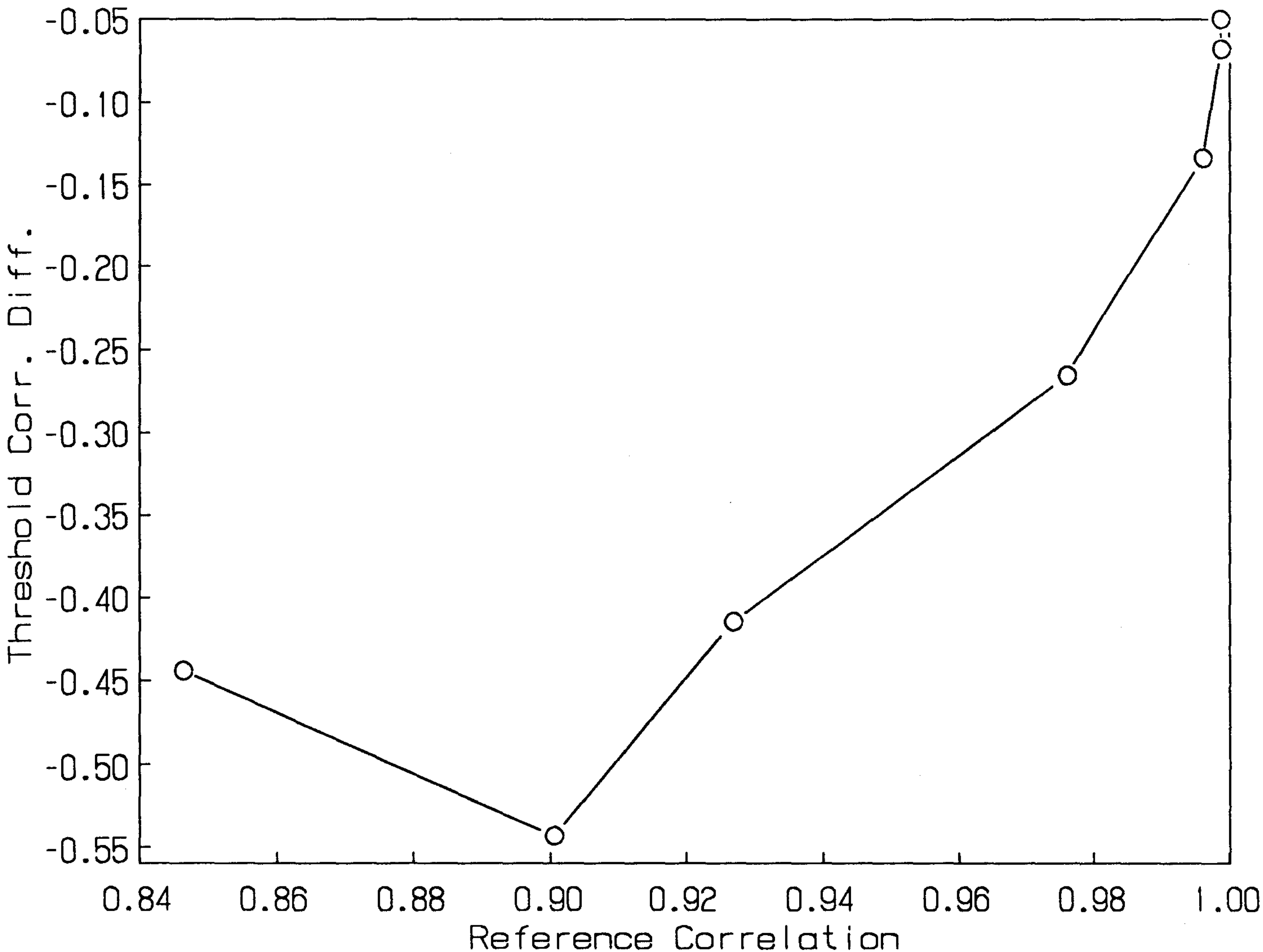
Outer Components Removed

BW	TRG. DELAY	CORR.	STD.DEV
500	None	.9999	-----
	Thresh.	.9667	.0119
300	None		
	Thresh.	.9624	.0132
200	None		
	Thresh.	.9526	.0252
100	None	.9924	.0022
	Thresh.	.9727	.0080

condition. We will consider conditions in which the interaural phases outside of the diotic band were randomized, since in this condition thresholds were affected by diotic bandwidth. Correlations were computed for stimuli with and without the dichotic pitch. For computation of correlations with the dichotic pitch (labelled thresh.), the average threshold narrowband delay at each diotic bandwidth from the three subjects was used. Figure 6 shows the correlations plotted as threshold decorrelation as a function of the reference correlation. The slope of the curve at very high reference correlations (.9758, representing the 200-Hz condition, and above) suggests that the auditory system is not simply comparing the correlation of the output of a single pair of filters between target and non-target intervals, since a narrow range of reference conditions produces a relatively wide range of threshold decorrelations. Further, the difference in threshold decorrelation between reference correlations of .9988 and .8462 ranges from .04 to .44. This was equivalent to the difference found by Gabriel and Colburn (1981) between reference correlations of 1.0 and 0.0, though they used different methods of decorrelation. All in all, support is provided for the notion that the auditory system combines information about interaural parameters from more than one peripheral filter.

If the assumption is made that the effects of interaural phase randomization on the cross-correlation function do not differ with frequency (that is, randomization has equivalent effects at 400 and 700 Hz, for example), then some estimation of the shape of a binaural weighting function can be made. Assuming that the dichotic pitch thresholds depend on the proportion of the noise within the weighting

Figure 6. Threshold decorrelations are plotted as a function of reference interaural correlation. Each symbol represents a separate condition, and the reference correlations decrease monotonically with bandwidth. Computations are based on the output of filters centered on 500 Hz.


-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
-0.40
-0.45
-0.50
-0.55
Threshold Corr. Diff.
0.84
0.86
0.88
0.90
0.92
0.94
0.96
0.98
1.00
Reference Correlation

function that is diotic, then data predictions can be made for different weighting functions. A rectangular weighting function would yield thresholds that were constant at diotic bandwidths greater than the width of the function, and would increase linearly as the interaurally randomized noise was brought closer to the CF of the target. On the other hand, a triangular weighting function would yield thresholds that increased at a greater rate as the diotic bandwidth was made increasingly narrow. These predictions are based on the shapes of the derivatives of the rectangle and triangle, respectively. Though transformations of the data into weighting functions were not performed, it would appear that the binaural weighting function is somewhat triangular in shape. However, since the dichotic pitch is not produced by an increase in signal energy, the effects of the randomized phases cannot be used to extrapolate an integration function described in terms of the bandwidth of the function some number of dB down the skirts, as peripheral filters usually are.

EXPERIMENT III

Experiment II provided reason to believe that a cohesive background noise is required in order for a dichotic pitch to be perceived. In that experiment, the effectiveness of the background noise was decreased by manipulations in the frequency domain. Another possible factor determining the perception of a dichotic pitch is the stability of the background noise across time.

A number of studies measuring detection thresholds for pulsed tonal signals masked by wideband noise have shown that the masking level difference is greater when the masking noise is continuous rather than pulsed. Yost (1985), for example, found that having a continuous masker increased the MLD by as much as 8.2 dB compared to the condition where both masker and signal were pulsed on simultaneously. The difference between thresholds with pulsed and continuous maskers for the diotic (N_oS_o) condition was found to be 1.9 dB, while in the dichotic (N_oS_π) condition, the difference was 10.1 dB, suggesting that the fringe is primarily helpful in binaural tasks. The beneficial effect of the fringe in binaural tasks was found to be dependant upon its duration, with overall MLD increasing steadily with fringe duration. At a fringe duration of 500 ms, thresholds were equivalent to the continuous condition. In the same study, Yost (1985) varied the interaural parameters of the noise fringe. Thresholds did not decrease if the fringe was presented monaurally ($F_mN_oS_\pi$), as uncorrelated noise ($F_uN_oS_\pi$), or if the interaural phase shift of the fringe was different than that of the masker ($F_\pi N_0 S_\pi$).

One way to consider the output of a filter with wideband noise as its input is as similar to a sinusoid that varies slowly in amplitude and phase (Webster, 1951). If two identical noises are presented to the two ears, there would not be any interaural phase and level differences between these two waveforms (the outputs of the peripheral filters). However, when an interaurally out-of-phase signal is added to the noise, the phase and level of the resultant (output) waveform will be changed differently in each ear. Interaural differences in phase and level are created when the interaural phase of the signal and the masker are not equal. Improved performance is seen in antiphasic conditions because these additional cues are available to the listener.

Detection ability improves when there is a fringe because the addition of the signal results in changes in interaural time and level in the waveform at that frequency. The fringe does not improve performance as much in the homophasic conditions since the introduction of the signal only creates a change in the signal-to-noise ratio and not changes in interaural parameters.

If detection of a dichotic pitch is dependent on distinguishing the interaural parameters of the narrow delayed band as different from the established diotic background noise, and the dynamic changes of the interaural parameters caused by the target provides additional cues for detection, then performance should be best when the interaural parameters of the fringe are the same as the background noise when the dichotic pitch is presented, and the fringe is continuous. If the fringe is different than the background noise during the observation interval, then additional changes in the interaural configuration are present that are not relevant to the task. These additional changes, if the binaural processor cannot ignore them, may detract from the subject's ability to detect the target. The ability of the listener to ignore interaural changes not relevant to detection of the dichotic pitch may depend on the frequency at which these interaural changes take place.

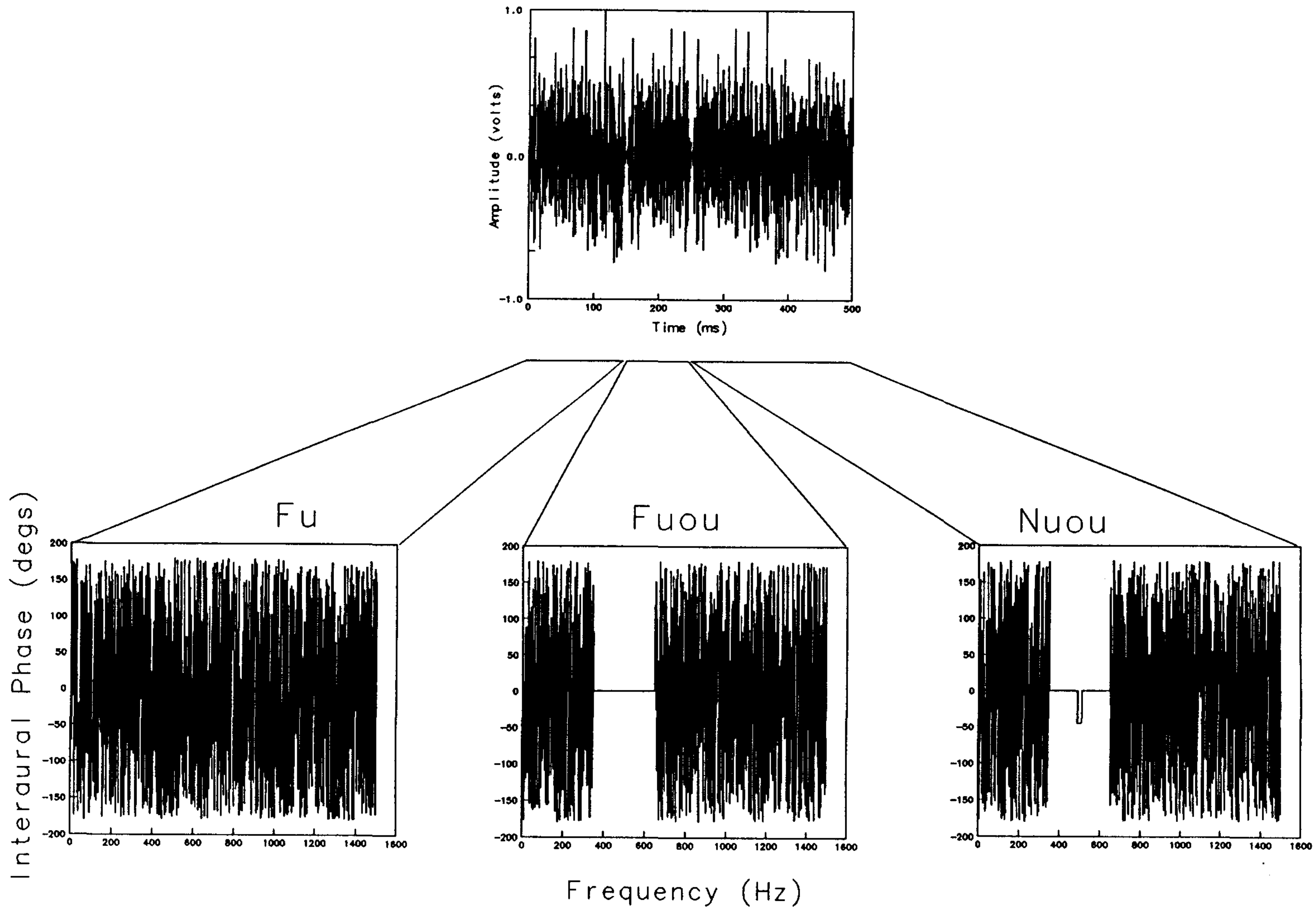
Experiment III investigated this possibility by manipulating the interaural parameters of the fringe in two of the conditions used in the previous experiment. In Experiment II, the fringe consisted of 250 ms of noise with the same interaural configuration as the noise that which served as a background for the dichotic pitch. In other words, the fringe was diotic within the inner band, and interaurally uncorrelated outside of this band (the width of which varied with condition). In the present experiment, a portion of the front end of the fringe was presented as completely uncorrelated noise; that is, interaural phases were randomized at all frequencies. Using the traditional subscripts to describe interaural parameters, then, a trial would consist of F_u, then F_{uou}[4], and then N_{uou} in which the dichotic pitch would be presented. The conditions were labeled by the length of relevant fringe, so that the results from Experiment II served as the 250-ms condition.

METHODS III

The methods used in this experiment were essentially identical to those used in Experiment II. The manipulated variable was the duration of the relevant forward fringe, which is defined as having the same interaural configuration as the noise which served as a background for the dichotic pitch. The rest of the 250-ms fringe contained noise uncorrelated at the two ears, and was generated by selecting independent random starting phases for each frequency component at each ear from a rectangular distribution. Thresholds were obtained at relevant fringe durations of 0, 50, and 100 ms. The duration of the completely uncorrelated fringe in each of these condition was 250, 200, and 150 ms, respectively. The appropriate conditions from Experiment II served as the 250-ms condition. A diagram of the interaural configuration of a complete trial is shown for the 100-ms condition in Figure 7. The experiment was conducted using two inner bandwidths from Experiment II, 300 and 500 Hz.

All other aspects of the experiment were identical to the previous experiment. Each section of noise (F_u, F_{uou}, and N_{uou}) was gated on and off using 5-ms $\cos^2$ ramps. The subjects from Experiment II also served in this experiment.

Figure 7. Interaural configurations for each section of a signal trial are shown. The top panel represents the time domain waveform. The first lower panel shows the irrelevant fringe, in which all interaural phases are randomized. The center panel shows the relevant fringe, in which the noise comprising the background is diotic. The third panel shows the diotic background with the diotic pitch centered in it.


Amplitude (volts)
Time (ms)
Fu
Fuou
Nuou
Interaural Phase (degs)
Frequency (Hz)

RESULTS III

Figure 8 shows the results of Experiment III for the same three subjects as in Experiment II. Panel 8a shows the data for the 300-Hz condition (in which the interaural phases of frequencies outside of the 300-Hz diotic band are randomized), and panel 8b shows the data for the 500-Hz condition. Threshold interaural delays of the target band are plotted as a function of the duration of the relevant fringe; that is, the duration of fringe having the same interaural parameters as the noise in the observation interval (except for the dichotic pitch). Different line types represent different subjects. The same symbols used in Experiment II are used in this figure.

The results are similar for all subjects in both conditions. Thresholds were lowest in the 250-ms condition, where the entire fringe is comprised of F_{uou} noise, and highest when the fringe is entirely F_u noise. The three horizontal lines in each panel represent the subjects' thresholds when there was no fringe - each interval was only 250 ms, with the dichotic pitch present for the entire duration in the target interval. In all conditions this threshold fell between those for the extreme fringe conditions. For subject MR, the crossover falls between the 0-and 50-ms conditions, for subject DM, it falls between the 50- and 100-ms conditions, and for subject AB, in the 300-Hz condition, the crossover is between the 0- and 50-ms conditions, and in the 500-Hz condition, it falls between the 100- and 150-ms conditions.

Figure 8. Threshold interaural delays for dichotic pitch detection are plotted as a function of the duration of the relevant fringe preceding the test interval. The top panel represents the 300-Hz condition (the width of the diotic background was 300 Hz), and the bottom panel represents the 500-Hz condition. Each different line type represents a subject. The horizontal lines show each subjects' threshold when no fringe was present.

Fig. 8a

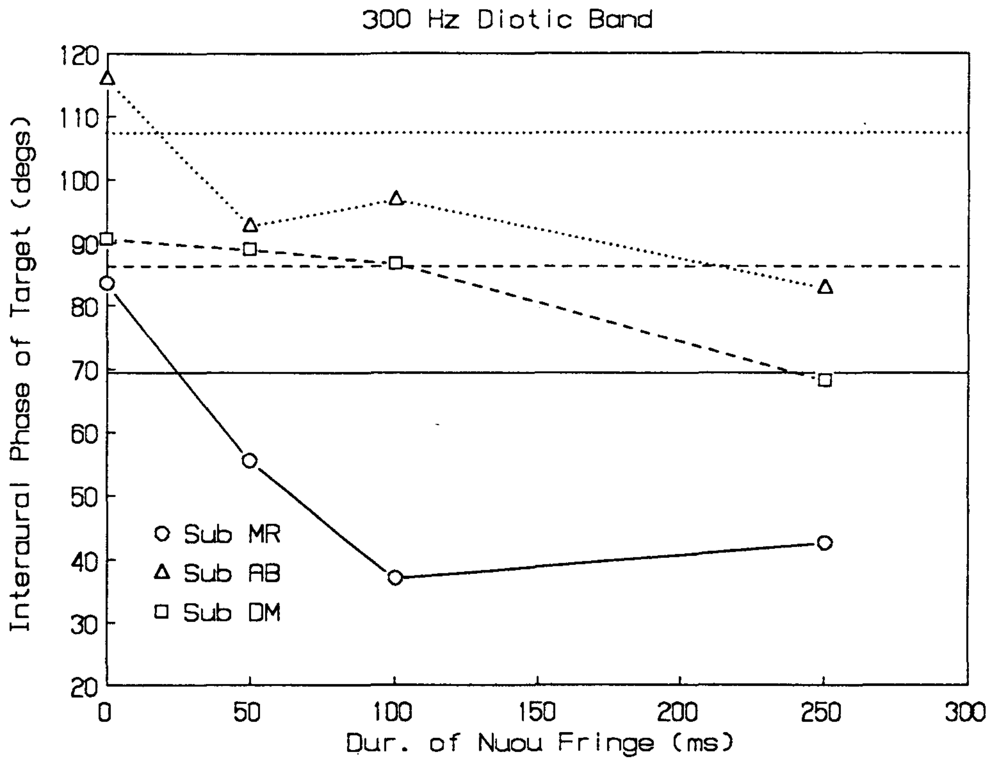
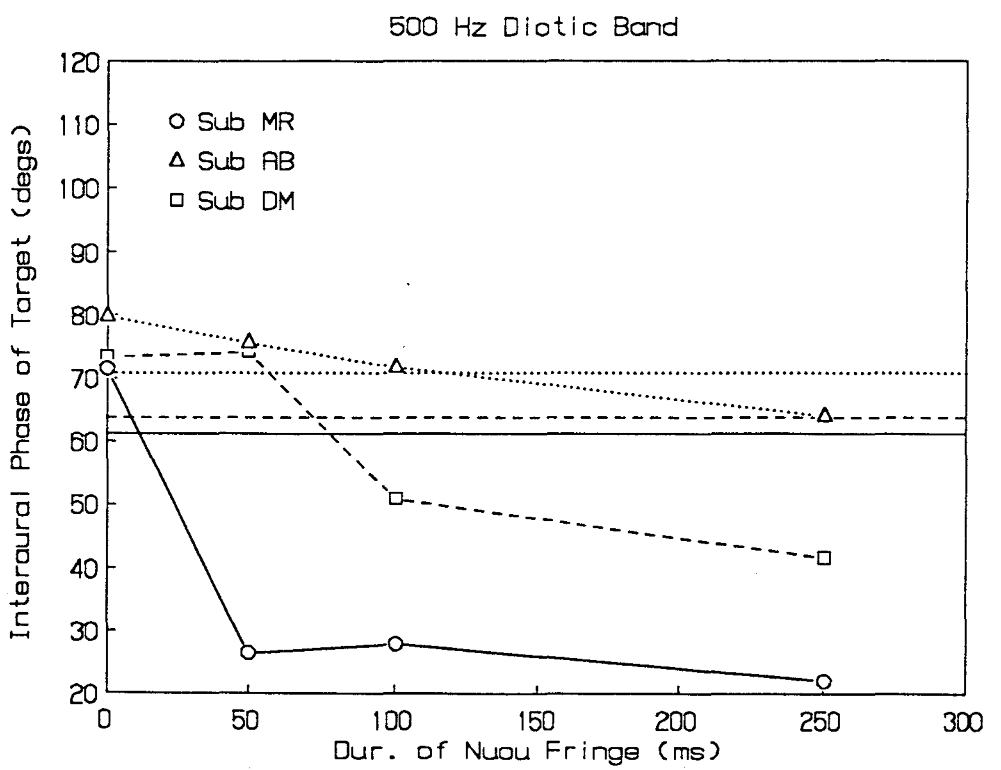

300 Hz Diotic Band
Interaural Phase of Target (degs)
120
110
100
90
80
70
60
50
40
30
20
0
50
100
150
200
250
300
Dur. of Nuou Fringe (ms)
Sub MR
Sub AB
Sub DM

Fig. 8b


500 Hz Diotic Band
Interaural Phase of Target (degs)
120
110
100
90
80
70
60
50
40
30
20
0
50
100
150
200
250
300
Dur. of Nuou Fringe (ms)
Sub MR
Sub AB
Sub DM

DISCUSSION III

The results in this experiment are consistent with those obtained by Yost (1985), using the MLD. If the diotic noise serves as a background against which the diotic pitch is "heard out", then the pattern of results makes intuitive sense. The F_{uou} fringe makes detection of the pitch easier, because the narrow band that is interaurally delayed has "moved" in intracranial space relative to the punctate background. If the fringe is completely uncorrelated (F_u), as it is in the 0-ms condition, then there is no salient background to move against, since the frequencies within the narrowband also have random interaural phases during this time. Interestingly, in these conditions, subjects required a greater delay to detect the pitch than with no fringe at all. This may have implications with the regard to the duration of the minimum binaural integration time (e.g., Grantham & Wightman, 1979). If the binaural processor is constrained by a temporal window that is, for example, triangular or gaussian in shape, then in the 250-ms condition of this experiment, best performance could be attained by centering the window on the point of transition (250 ms into the trial). Only one interaural change takes place, and it is centered within the window. In other conditions, however, if the fringe interaural transitions from F_u to F_{uou} take place within the temporal window, then they may interfere with processing of the target interaural transition. In these conditions, the optimal placement of the window may not be the center of the transition point, but displaced in time toward the end of the trial. Finally, in the 0-ms condition, it may be optimal to ignore the dynamic changes altogether since they all occur simultaneously. The results of this experiment suggest that the binaural system cannot accomplish this, and that at least part of the temporal window is placed on the transition point.

Thresholds increased nearly monotonically as the duration of the relevant fringe was decreased. In all but 4 of the 18 (3 subs x 3 duration changes x 2 diotic bandwidths) changes in relevant fringe duration, the pattern held, and in those 4 cases, the decrease in threshold was less than 5°.

GENERAL DISCUSSION

There are several conclusions that can be made as a result of these experiments.

1. Information about interaural parameters is combined across frequency channels; that is, the auditory system looks at the outputs of more than one peripheral filter in these conditions.

2. Dichotic pitches are created by differences between the interaural parameters of the interaurally delayed narrow band and those of the surrounding noise. The more stable the interaural parameters of the background noise across a wide range of frequencies, the easier it is for The auditory system to separate the dichotic pitch from the noise.

3. The effectiveness of the noise surrounding the dichotic pitch as a background is determined by the stability of the interaural parameters of the noise, both over frequency and over time.

Experiment I provided evidence that irregularities in the interaural configuration of the background noise could indeed impair processing of the interaural parameters of a target band. However, the effects caused by the distractor dichotic pitch could also be explained assuming processing of only one pair of frequency-matched peripheral filters. Such an explanation would assume that the dichotic pitch in the target interval decorrelates the outputs from the two filters. As the CF of the distractor pitch is moved closer to that of the target, the reference interaural correlation (the correlation in the non-target interval) is decreased. Previous studies have found that the jnd's in interaural decorrelation increase as the reference correlation decreases (Gabriel & Colburn, 1981). The interaural correlation of a pair of filters can be effected substantially by changes in interaural parameters of frequencies well down in the skirts of the filters (Kohlrausch, 1988). This explanation cannot be ruled out by the results of Experiment I.

In contrast, the results of Experiment II clearly show that performance begins to deteriorate when randomization of interaural phase is introduced at frequencies remote from the target, even when the diotic noise surrounding the target pitch is 300-400 Hz wide. This is much wider than the estimated bandwidth of the peripheral filters centered on 500 Hz. The average interaural correlation in the 300-Hz condition, when the target was not present, was still above .995. Since, in the 900-, 700-, 500-, and 300-Hz conditions the reference correlation of the peripheral filters centered on the target CF remains constant, and yet the threshold interaural decorrelation increase across these conditions, it is likely that the auditory system is not simply monitoring one set of peripheral filters.

In order for a dichotic pitch to be perceived, a stable background noise must be provided. Stability in the frequency domain, which was manipulated in Experiments I and II, is at least partly determined by the homogeneity of the interaural parameters across frequency components. In Experiment III, manipulation of the stability of the background noise occurred in the time domain. This was accomplished by providing a forward fringe for the observation interval. It was assumed that the fringe that resulted in the best performance would be noise with interaural parameters identical to the observation interval. When comparisons were made with thresholds obtained when no fringe was present, the results show clearly that performance improves as the length of time that the fringe is identical to the observation interval is increased. With a 250-ms observation interval, thresholds continued to decrease as the duration of identical fringe was increased out to 250 ms.

If binaural information is integrated over a window in time, the auditory system may be able to center the window over the period of the stimulus which will result in a maximization of the dissimilarity between the non-target and target intervals. Further investigation into this question may make use of a backward fringe as well, so that the optimal placement of the integration window would always be centered on the observation interval. This procedure may allow for an accurate estimation of the duration of the window. An interesting aspect of the data from Experiment III is that when the entire fringe was interaurally uncorrelated, thresholds were higher than in conditions with no fringe at all. This may suggest that the integration window is at least 250 ms in duration.

Comparisons have been made in these experiments between results obtained using dichotic pitch stimuli and those obtained using the MLD. Although strong similarities exist between the two, there are advantages to using the dichotic pitch.

One problem with the MLD is that it is expressed as a difference between two dissimilar processes. The standard of performance (N_oS_o or N_mS_m) is presumably a measure of an energy detection process, whereas performance in binaural conditions is a result of the interaural parameters of the stimuli, as well as an energy detection component. There is no guarantee, however, that the energy detection component in binaural tasks is equivalent to that in diotic or monaural tasks. It cannot be assumed, therefore, that the differences in threshold seen in binaural conditions are solely the result of binaural processing.

Another possible problem with the MLD paradigm is that the experimenter generally does not have control over the precise interaural differences of time and level in the stimulus. While the level and interaural phase of the signal to be added to the noise can be manipulated, the resultant waveform that the ear receives is determined by the addition of the signal and the noise component at that frequency, the interaural parameters of which are generally not known to the experimenter. This may be a particular problem in tracking procedures, because as the signal level decreases, the resultant level and phase of the overall waveform will be increasingly affected by the parameters of the noise component, which are random.

While it is true that any dichotic pitch stimulus could be produced by the addition of a narrowband noise, as opposed to manipulating the phase of the existing noise waveform, it would be extremely impractical to do so. On each trial, the phase and level of the signal as well as the phase and level of the noise components at the frequencies of the signal would have to be determined, so that the combination of signal and noise that would result in a phase delay only could be calculated. On the other hand, dichotic pitches afford the experimenter not only ease in generation of stimuli, but precise knowledge of the noise presented to the subject's ears.

Endnotes:

1 For the noise, the <u>π</u> subscripts indicate the interaural phase of the outer band, the <u>o</u> subscript indicates the interaural phase of the inner band.

2 As in endnote 1, the subscripts describe the interaural parameters of the noise below the inner frequency band, within the inner band, and above the inner band. The <u>u</u> subscripts denote interaurally uncorrelated noise, and the <u>o</u> subscript denotes interaurally in-phase noise.

3 Correlations were computed on the outputs of computer simulated auditory filters, based on the model of Patterson & Nimmi-Smith (1987).

4 The F_{uou} noise is identical to the N_{uou} noise. It is labelled separately since the signal (a narrow band phase shift) can only occur during the observation interval (N_{uou}).

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The thesis is therefore accepted in partial fulfillment of the requirements for the degree of Master of Arts.

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