Lateralization of bands of noise: Effects of bandwidth and differences of interaural time and phase

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The effects of stimulus bandwidth on lateralization of narrow bands of noise were investigated with an acoustic pointing task. Stimuli were narrow bands of noise (centered on 500 Hz with bandwidths ranging from 50–400 Hz) that contained interaural time delays and/or interaural phase shifts. The overall extent of lateralization and sidedness was found to vary greatly as a function of stimulus bandwidth, as insightfully discussed earlier by Jeffress [L. A. Jeffress, *Foundations of Modern Auditory Theory*, edited by J. V. Tobias (Academic, New York, 1972)]. The data are qualitatively consistent with a weighted-image model [Stern *et al.*, J. Acoust. Soc. Am. **84**, 156–165 (1988)] that specifies and utilizes the shapes and locations of patterns of hypothesized neural activity. These patterns are topographically organized along a two-dimensional surface, and they describe the cross-correlation function of the stimuli as a joint function of frequency and the delay parameter of the cross-correlation operation. In this fashion, lateralization depends upon individual modes of such patterns that are weighed with respect to their straightness (consistency of interaural delay over frequency) and centrality (the extent to which interaural delays are small in magnitude).

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INTRODUCTION

In 1972, Jeffress described how the lateral position of an interaurally delayed stimulus depends upon bandwidth. He contrasted the lateral position of a 500-Hz tone delayed 2000 μs (a full period) with that of a broadband noise interaurally delayed by the same amount. He noted that the pure tone is judged to be "centered," while the broadband noise is perceived far toward the leading ear. Jeffress (1972, pp. 357–358) explained this result by noting that neural activity in the central auditory system that processes such stimuli (i.e., the so-called "coincidence detectors") is weighted differentially with regard to interaural delay. Cells which monitor stimuli that produce small interaural delays were assumed to outnumber those that process stimuli containing large interaural delays. For narrow-band stimuli, laterality judgments are assumed to be dominated by the activity of neurons that process stimuli with very small interaural delays. For broadband stimuli, laterality is dominated by neural activity that now reflects the contribution of additional neurons that respond to the added spectral components. These additional neurons have in common an internal delay that corresponds to the external delay of the stimulus. In this fashion, it is postulated that a large amount of neural activity, all indicating a consistent amount of delay over a range of frequencies, dominates more sparse activity produced by neurons that monitor other delays. The spatial density of neurons that process interaural delays is incorporated within virtually all modern models of binaural processing (e.g., Sayers and Cherry, 1957; Colburn, 1977; Blauert and Cobben, 1978; Stern and Colburn, 1978), and physiological data concerning the distribution of such neurons has been provided by Kuwada and Yin (1983) and Kuwada *et al.* (1987). In addition, the concept of density of coincidence-counting neurons has been used to explain certain psychophysical observations. For example, it is well known that small changes in the position of sources of sound are more easily noted when the sounds originate in the median plane than when they originate from positions near to or opposite each ear.

These statements notwithstanding, it appears that Jeffress' observations concerning bandwidth have not appeared to have stimulated empirical and theoretical investigations that focus upon how the binaural processing of an interaurally delayed stimulus is affected by bandwidth. The purpose of this paper is to reopen these issues and to examine lateralization as a function of bandwidth utilizing stimuli that incorporate interaural time delays and interaural phase shifts. In addition, we will discuss these data in terms of a new model of binaural hearing that addresses these data and suggests a new way of interpreting arguments concerning the role of envelope versus fine structure in the formation of acoustic spatial images (Stern *et al.*, 1988). Because Stern *et al.* describe the new model in detail, discussions of it will be directed toward conceptual rather than quantitative explanations.

In the following sections, we first review some of the conceptual aspects of the model and the consequent motivation for the particular stimuli that were used in the experiments. We then present the data and evaluate the model in general terms.

I. THE WEIGHTED-IMAGE MODEL

The model, which is called the weighted-image model, addresses the lateralization of spectrally and temporally complex stimuli in terms of the patterns of activity of the putative coincidence detectors at different frequencies. As is true for most other models of binaural interaction, the weighted-image model assumes that peripheral auditory processing can be modeled (at least in part) by passing signals to each ear through a bank of parallel bandpass filters, each with a slightly different center frequency. Outputs of pairs of these filters with matching center frequency, one from each ear, are then cross correlated. Figure 1 is a plot of the locations of the *maxima* of the resulting cross-correlation function of a broadband noise with a 1500-μs interaural temporal difference (ITD) after such bandpass filtering. The horizontal axis represents interaural delay (τ) and is the argument of the cross-correlation function. The vertical axis indicates the center frequencies of the bandpass filter (f). The frequency of 500 Hz is indicated by the horizontal broken line.

If the bandwidth of a stimulus centered at 500 Hz were sufficiently broad, the ITD would be readily identifiable because the locus of the peaks is a straight and vertical line at only the value of the interaural delay parameter τ corresponding to that ITD (1500 μs in this case). This "straightness" could very well be the cue used to recognize that the interaural delay of the stimulus is exactly 1500 μs. Since real sounds emitted by point sources produce ITDs that are consistent over a range of frequencies, the "straighter" a particular line or trajectory of maxima, the more that trajectory is likely to represent the actual ITD of the stimulus. On the other hand, if the signal were very narrow in bandwidth, one could conjecture that the auditory system would have difficulty distinguishing between the various peaks because there is not enough range of frequencies to estimate adequately the "straightness" of any single trajectory. Under these circumstances, it seems that lateralization is determined by the trajectory that is closest to the f axis, i.e., the most "central" locus of maxima. As discussed above, it is believed that the more central trajectories are weighted more heavily because there are more binaural coincidence-counting units with small internal interaural delays than there are neural units with larger internal delays. Jeffress (1972) focused upon centrality and did not discuss straightness *per se* nor how both centrality and straightness could be manipulated so that their respective effects and interactions could be discovered and quantified.

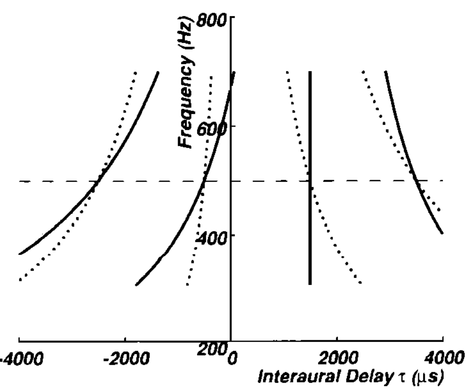

FIG. 1. Location of the peaks of the cross-correlation function following peripheral bandpass filtering for noise with an ITD of 1500 μs and zero IPD (solid curves) and an IPD of 270 deg and zero ITD (dotted curves). The vertical axis indicates the center frequency of the bandpass filters, while the horizontal axis indicates the argument of the cross-correlation function. Note that these two combinations of ITD and IPD produce maxima for the same values of τ at 500 Hz.

In many cases (including the 500-Hz noise with a 1500-μs ITD), either straightness or centrality considered in isolation would cause the sound to be lateralized toward different sides of the head. It seems reasonable to believe that, in these cases, lateral position is the result of some type of resolution of these conflicting pieces of information (perhaps not unlike the "trade" of interaural timing and intensity information that characterizes the lateralization of simple stimuli with small interaural differences).

In order to examine the extent to which straightness plays a role in the lateralization of complex stimuli, it is useful to consider the lateral position of 500-Hz bandpass noise as a function of both ITD and interaural phase difference (IPD). These stimuli are particularly illuminating because appropriate combinations of ITD and IPD enable the experimenter to manipulate the interaural correlation of a binaural bandpass noise such that straightness and centrality can be *independently specified* over spectral regions of interest. Specifically, consider a bandpass noise presented with an ITD of T_s and an IPD of ϕ_s. We adopt the notational convention that a positive ITD or IPD causes the signal to the left ear to lag the signal to the right ear in time or phase. Assuming ergodicity, we define the cross-correlation function of the stimuli to be

$$R_s(\tau) = E\,[s_L(t)s_R(t-\tau)] = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} s_L(t)s_R(t-\tau)dt\,, \quad (1)$$

where $s_L(t)$ and $s_R(t)$ are the signals to the left and right ears, respectively.[1] As the signals undergo peripheral bandpass filtering, the predictions of the model are derived from the cross-correlation function of the outputs of the bandpass filters as a function of their characteristic frequency f. It is easy to show that the maxima of the cross-correlation function of the outputs of peripheral filters with center frequency f will occur at values of the interaural delay parameter τ equal to

$$\tau = T_s + (\phi_s/2\pi f) + (k/f)\,,$$

where k is an integer. A maximum of the cross-correlation function will appear at τ equals some arbitrary T_d at frequency f if values of T_s and ϕ_s are chosen such that

$$T_s = T_d - (\phi_s/2\pi f) - (k/f)\,. \quad (2)$$

The parameter ϕ_s controls the straightness of the trajectory, and changing the value of ϕ_s causes the trajectories to "twist" nonlinearly in the τ-f plane, and to translate along the τ axis. Varying the value of T_s causes the trajectories to translate along the τ axis without changing their shape. For example, if ϕ_s equals 0 rad, there is a trajectory that is perfectly straight for τ equals T_s (as in the solid curves of Fig. 1). If, on the other hand, ϕ_s equals 270 deg, and, if T_s is selected according to Eq. (2), the correlation function will include a trajectory of maxima that also passes through τ equals T_s at frequency f, but that trajectory will be less "straight" (as in the dotted curves of Fig. 1).

In general, we expect that the position of the perceived image will be dominated by centrality considerations when the stimuli are presented with sufficiently narrow bandwidths. In the limiting case, very narrow-band noise stimuli produce spectra that are like those produced by pure tones. Since all of the trajectories of cross-correlation maxima for pure tones will be completely straight and parallel to one another, no single trajectory would be weighted more than any of the others, and the image location would be mediated by the relative centrality of these trajectories. In addition, it is difficult to obtain reliable estimates of the curvature of the trajectories of limited spectral extent produced by a narrowband stimulus. In order for curved trajectories to be produced, the stimulus bandwidth must be wide enough for some stimulus components to be weighted more heavily than others by the filters of the peripheral auditory system. Hence, the contributions of straightness considerations to lateral position should become increasingly more important as bandwidth increases.

In the present paper, we describe the results of two sets of lateralization experiments. The first compares the lateralization of two sets of stimuli with equal centrality but different curvature, while the second provides data using a wider variety of stimulus conditions in which straightness and centrality are varied simultaneously while the interaural delay of the envelope (the group delay) is held constant.

II. EXPERIMENTAL PROCEDURE

An acoustic pointing task was employed in which listeners varied the interaural intensitive difference (IID) of a 200-Hz-wide band of noise centered at 500 Hz (the pointer) so that it coincided with or matched the intracranial position of a second experimenter-controlled stimulus (the target). This procedure has been used in several previous studies (e.g., Bernstein and Trahiotis, 1985a,b; Trahiotis and Bernstein, 1986) and is described fully in Bernstein and Trahiotis (1985a). Listeners varied the intracranial position of the pointer by means of an adjustable potentiometer, which resulted in an IID (by increasing the intensity in one ear and decreasing it in the other) of the pointer across a pair of matched TDH-39 earphones. An arbitrary and randomly chosen value of IID was inserted in the pointer prior to each adjustment. This served to randomize the position of the potentiometer's knob that yielded an IID of zero dB, and made it impossible for the listeners to rely on the absolute position of the knob within and across conditions.

The ITDs and IPDs of the targets were fixed within trials and were produced by inserting either a passive delay line or a phase shifter (or both) in the right channel. Both delayed (and possibly phase shifted) and undelayed channels were then passed through identical electronic switches that were gated on and off simultaneously (i.e., there were no onset or offset disparities).

Each sequence of stimuli consisted of three presentations of the target followed by three presentations of the pointer, each of duration 100 ms, separated by 50 ms, and followed by a 400-ms pause. All stimuli were gated with 10-ms cosine-squared rise/decay times. Targets presented with a bandwidth of 100 Hz were presented at an overall level of 70 dB SPL, and stimuli with other bandwidths were manipulated to maintain a constant noise power per cycle. When the IID of the pointer was zero, the total power at each ear was 73 dB SPL. The sequencing repeated indefinitely until the listeners indicated that they had matched the positions of the target and pointer.

While making a match, listeners were able to halt the stimuli and to "check" their adjustments after a period of silence. The ability to stop a sequence, rest, and restart appeared to be very helpful. When the listeners indicated that they had completed a match (by pressing a button on their response box), the sequencing stopped and a tone was inserted in the circuit as a substitute for the noisy pointer to facilitate measurement of the IID. The IID so measured served as a metric of the intracranial position of the target. The parameters of the target were fixed during a session that typically lasted about 40 min. Listeners positioned the earphones only once per session. One of the conditions run during each session contained the target presented diotically. The mean IID (typically on the order of a dB or so) inserted by the listener to match the position of the diotic target served as a "correction factor" and was subtracted from the IIDs obtained under all other conditions. Such "calibrating" has been found to provide excellent test/retest reliability across sessions in these types of experiments (Bernstein and Trahiotis, 1985a,b; Trahiotis and Bernstein, 1986). At the beginning of each 1-h session, the listener, who was seated in a sound-deaded room, made three "practice" adjustments in order to become refamiliarized with the procedure. Values of ITD and IPD were pseudorandomly presented within and across sessions and different orders of presentation were given to each listener.

Two female and two male listeners participated in this study. All were young adults who had extensive prior experience in similar experiments including those described in Trahiotis and Bernstein (1986).

III. EXPERIMENT I

In this experiment we measured the subjective lateral position of bandpass noises with a center frequency of 500 Hz with bandwidths of 50, 100, 200, or 400 Hz for two conditions: (1) an ITD of 1500 μs and (2) an IPD of 270 deg. Of course, the ITD is equivalent to an IPD that is a linear function of frequency. On the other hand, an IPD is equivalent to an ITD which is inversely proportional to frequency, as depicted in Fig. 1. The IPD of 270 deg may also be thought of as a delay of only the carrier of the bandpass noise, while the ITD may be thought of as a consistent delay of the constituents of the whole waveform (i.e., the envelope, the carrier, and the phase modulation). Note that both the ITD of 1500 μs and the IPD of 270 deg produce identical interaural delays for stimulus components at 500 Hz (as is seen in Fig. 1). Thus, within a narrow region around 500 Hz, the trajectories of maxima of the cross-correlation function exhibit equal centrality but different straightness for these two classes of stimuli.

For the stimuli presented with the 1500-μs ITD, the most central trajectory of maxima of the correlation function is positioned (at 500 Hz) at $-500\,\mu$s (on the left or "lagging" side of the head), but the straightest trajectory is positioned at $+1500\,\mu$s (on the right side). For very narrow bands of noise, which approach pure tones, it is well known that listeners' lateralization judgments reflect the location of the more central trajectory. It was noted earlier that broad bands of noise similarly delayed are lateralized far toward the leading ear. Consequently, it was our expectation that the lateral position of the stimuli presented with the 1500-μs ITDs would change dramatically as a function of increasing bandwidth. On the other hand, the lateral position of the stimuli presented with the 270-deg phase shift would not be expected to be greatly affected by increases in bandwidth because both the most central and the straightest trajectory are on the left side of the head at a value of τ of about $-500\,\mu$s (as seen in Fig. 1).

Results from this experiment, using the procedures described in the previous sections, are plotted in Fig. 2 for each of the four listeners. The IID of the pointer that was used to match the position of the interaurally delayed target is plotted as a function of the bandwidth of the target. The notational conventions adopted for this experiment are such that positive IIDs represent images that were perceived toward the right side of the head (which are produced by "natural" broadband stimuli with negative ITDs).[2] To illustrate the excellent repeatability of these matches, the individual data points for three replications as well as the averaged data are shown.

Consistent with our expectations, the 50- and 100-Hz-wide bands of noise presented with an ITD of $1500\,\mu$s were lateralized toward the left side of the head by all listeners. The 400-Hz-wide band of noise, however, is lateralized toward the right side of the head by all of the listeners. Of particular interest are the individual differences in the amount of IID of the pointer used by each listener to match the position of the targets.

Listener BB used an IID of about -22 dB to match the position of the 50-Hz band of noise, and she used an IID of about $+24$ dB to match the position of the 400-Hz-wide band of noise. Clearly, the target moved from far left to far right as bandwidth was increased from 50 to 400 Hz. In fact, the 200-Hz-wide band of noise was matched by an IID of about $+15$ dB, indicating that the target moved from one side of the head to the other as bandwidth was increased from 100 to 200 Hz!

Listener PJ's data are similar in that the narrowest bands of noise indicate matches toward the left side of the head, while the 400-Hz band of noise is matched by a pointer IID of about $+14$ dB, which indicates that the target was heard far toward the right side of the head. Note that the 200-Hz-wide band of noise is matched by an IID of about 0 dB indicating that the target was heard close to the midline. While the 200-Hz-wide band of noise is heard at distinctly different places by BB and PJ, it should be noted that the bandwidth at which the image moves from the left to the right side of the head is not dramatically different for these two listeners.

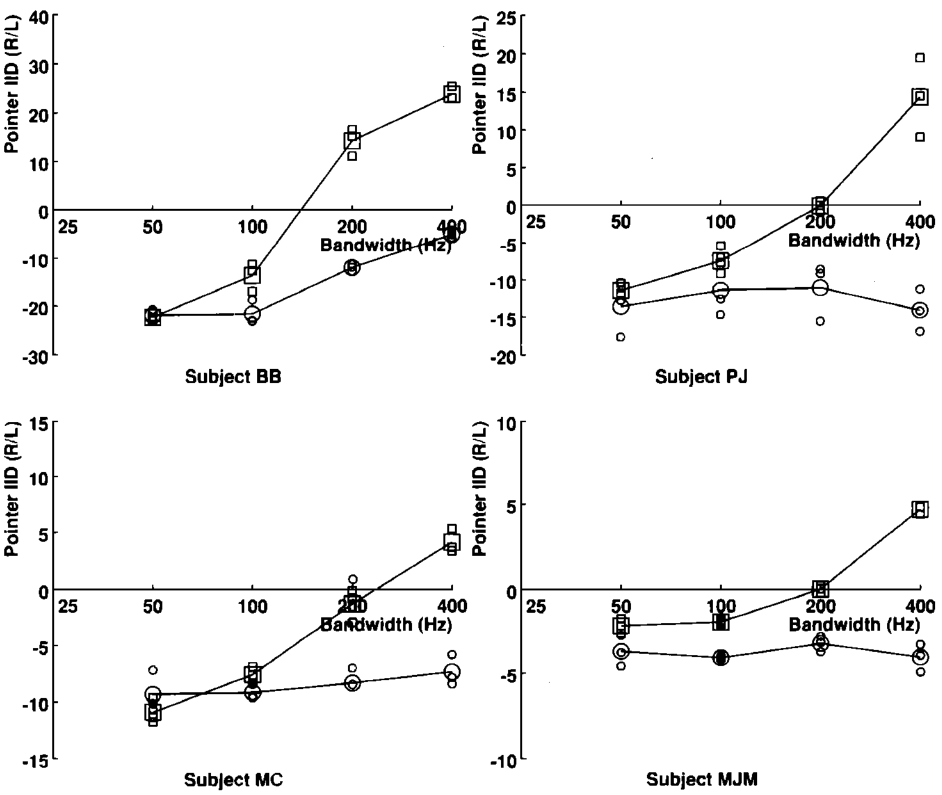

FIG. 2. Results of experiment I: pointer IID needed to match the position of the bandpass-noise target as a function of bandwidth. The center frequency of the target was 500 Hz. Targets were presented with either an ITD of 1500 μs and zero IPD (squares) or an IPD of 270 deg and zero ITD (circles). The larger symbols joined by the solid lines represent the mean of a set of three matches at each bandwidth; the smaller symbols represent individual matches. The four panels represent data obtained from each of four listeners.

The data obtained from listeners MC and MJM are somewhat different. Listener MC matched the 50- and 100-Hz bands of noise IIDs of about -11 and -8 dB, respectively, indicating images heard toward the left side of the head. The 400-Hz-wide band of noise was matched by an IID of only $+2$ dB, indicating that that target was heard toward the right (but not very far from the center of the head).

Listener MJM consistently used only very small values of IID, and her matches indicate that the 50-Hz-wide band of noise was heard slightly toward the left, while the 400-Hz band of noise was heard slightly toward the right. The bandwidth at which the target moved from one side of the head to the other was between 200 and 400 Hz for both MC and MJM.

The data of all listeners indicate that the laterality of targets presented with an ITD of 1500 μs depends upon bandwidth much in the manner that we had expected. Individual differences in the use of the pointer will be examined more closely after presenting the data obtained with interaurally phase-shifted targets.

When the targets were presented with an IPD of 270 deg, all of the matches indicate that the targets were heard on the left side of the head for all listeners, irrespective of bandwidth. In addition, for the 50-Hz-wide bands of noise, all listeners matched the position of the phase-shifted targets by utilizing essentially the same amount of IID that they had used to match the corresponding target containing an IID of 1500 μs. Listener BB required IIDs of about -22 dB or so to match the position of the phase-shifted 50- and 100-Hz-wide bands of noise. When the bandwidth was increased to 400 Hz, BB used an IID of -5 dB, indicating that the target had moved to a location closer to the midline (but was still heard on the left side of the head). These data are dramatically different from those obtained using noises with identical bandwidths but presented with an ITD of 1500 μs. Consistent with our expectations, the wider bands of noise that were interaurally phase shifted produced images that remained on the left side of the head, while their interaurally time delayed counterparts were heard far to the right of the head.

The data of listeners PJ, MC, and MJM are very consistent in that each of these listeners used relatively constant amounts of IID to match the phase-shifted targets, independent of the bandwidth. Once more, PJ and MC use relatively smaller amounts of IID to make their matches than did BB, but these two listeners, in turn, both use greater values of IID than did MJM who rather consistently used an IID of about -4 dB.

In general, both sets of data conform with our expectations regarding the effects of the competition between the centrality and curvature factors of the putative internal representation of the stimuli via a cross-correlation mechanism.[3]

IV. EXPERIMENT II

In order to study further the effects of interaural delays and phase shifts, we conducted a second experiment in which the ITD was held constant (at 1500 or 2000 μs) while the IPD was varied from 0 to 270 deg in 90-deg steps. As before, the bandwidth of the target was either 50, 100, 200, or 400 Hz. We used the same procedures and listeners as in experiment I.

Figure 3 shows the locations of the maxima of the cross-correlation functions of the stimuli used in experiment II, with the solid curves representing stimuli with 1500-μs ITDs and the dotted curves representing stimuli with 2000-μs ITDs. Again, these functions were calculated after passing the stimuli through parallel bandpass filters in order to include the major effects of frequency analysis performed by the peripheral auditory system. As before, the horizontal axis represents the internal delay (τ) of the cross-correlation function, while the vertical axis indicates the center frequency of the bandpass filters (f). As noted at the end of Sec. I, the curvature of the trajectories depends solely on the IPD of the stimuli. Their horizontal location, however, depends on *both* ITD and IPD. Again, we believe that the perceived location of the binaural targets depends on both the relative straightness and centrality of these trajectories. With this in mind, we now consider the qualitative trends of the experimental data.

Results from experiment II are plotted in Fig. 4 for ITDs of 1500 μs, and, in Fig. 5, for ITDs of 2000 μs, for each of the four listeners. As in Fig. 2, the IID of the pointer that was used to match the position of the target is plotted as a function of bandwidth, for each of the four values of IPD. Only the average of the three separate matches is shown because the variability of the data was quite small (i.e., the standard deviations of the matches was typically about one dB or so).

Considering first all data collected with an ITD of 1500 μs, we note that the data with an IPD of 0 deg replicate those presented in Fig. 2 for corresponding stimulus bandwidths, and they conform to our predictions as discussed in Sec. III.

Targets with an IPD of 90 deg added to the ITD of 1500 μs were perceived to be at or near the midline when the bandwidth of the target was either 50 or 100 Hz. As the bandwidth of these stimuli was increased to either 200 or 400 Hz, they were lateralized increasingly more toward the right side of the head. As was seen in experiment I, the listeners varied considerably in the amount of IID of the pointer required to match the position of the targets. Once again, listeners BB and MJM represented the extremes, BB showing the greatest range of response variation, and MJM the smallest range. These stimuli exhibit a central trajectory that passes through τ equals 0 μs at 500 Hz, so we expect that these narrow-band targets would be heard at or near the midline. As bandwidth is increased, it is expected that the targets would be heard further toward the right side because the trajectory that passes through 2000 μs at 500 Hz is the straightest. These expectations are, in fact, reflected in the data of all listeners.

When the IPD was increased to 180 deg, all of the listeners indicated that the targets were lateralized relatively far to the right side of the head, relatively independently of the bandwidth of the target. These stimuli are expected to be perceived toward the right side of the head for all bandwidths because the trajectory to the immediate right of the

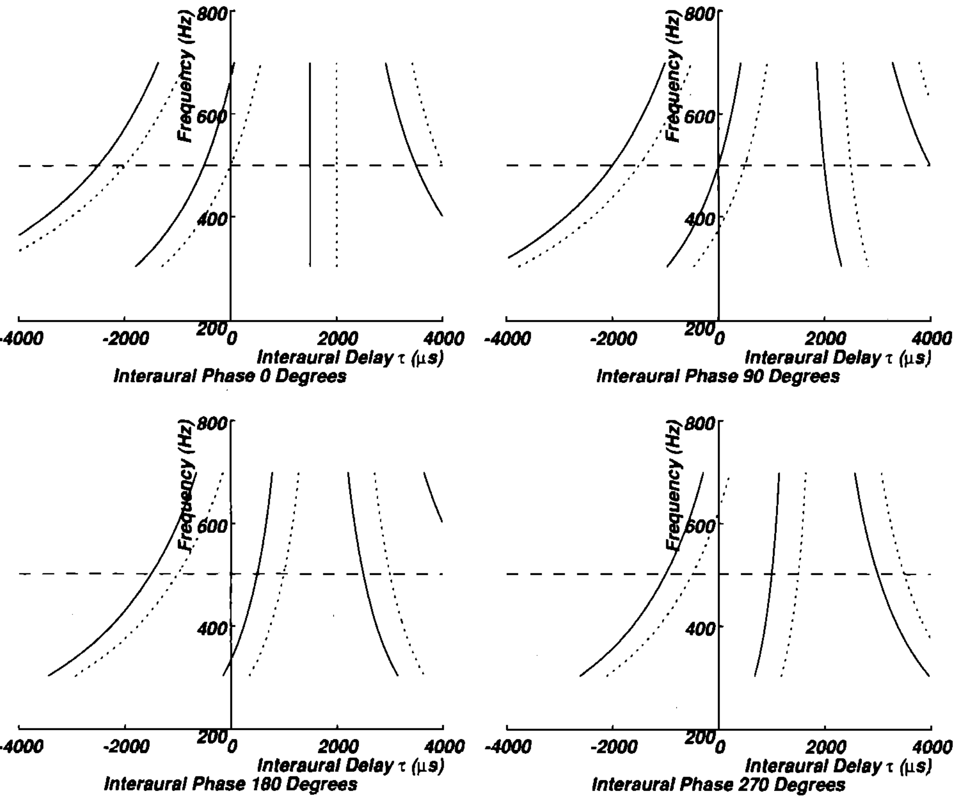

FIG. 3. Location of the peaks of the cross-correlation function following peripheral bandpass filtering for noise with an ITD of 1500 μs (solid curves) and an ITD of 2000 μs (dotted curves). The curves were plotted for values of the IPD of 0, 90, 180, and 270 degrees, as indicated.

vertical axis is both the straightest and the most central. Again, the data conform to these expectations.

Finally, when the IPD was 270 deg, three of the listeners (BB, PJ, and MJM) made matches which indicated that the targets were perceived consistently far toward the right ear, independent of bandwidth. Listener MC's data were different in that he matched the 50- and 100-Hz-wide targets to pointers with IIDs of about -5 and 0 dB, respectively. These matches indicate that the stimulus was first heard toward the left and then at the midline as bandwidth was in-

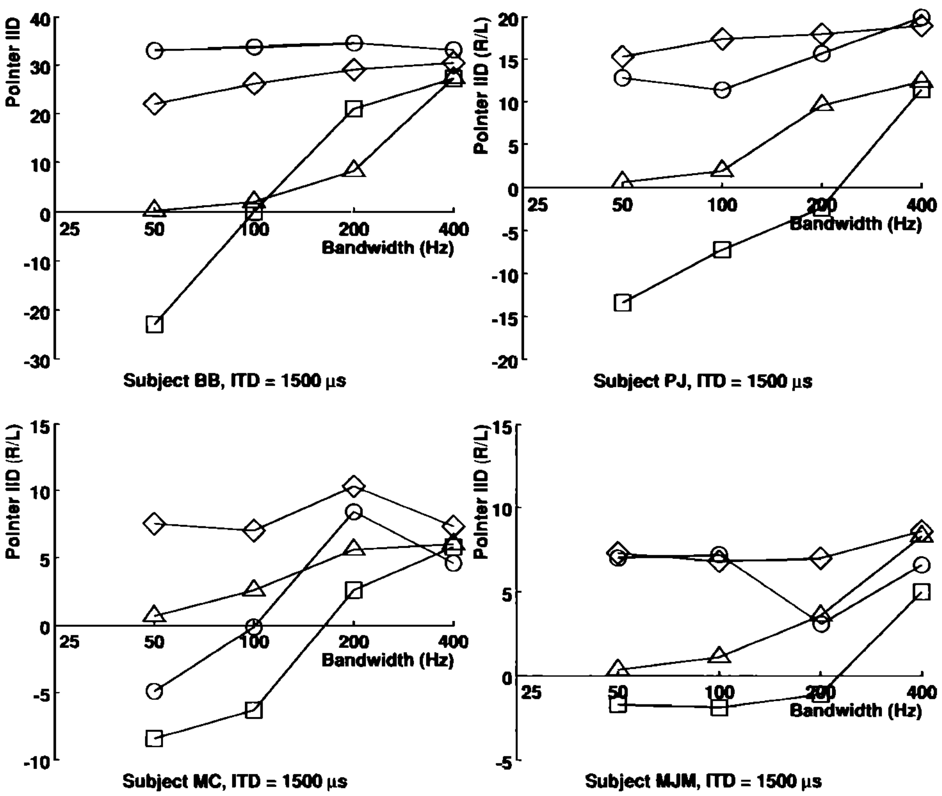

FIG. 4. Results of experiment II: pointed IID needed to match the position of the bandpass-noise target as a function of bandwidth. Targets were presented with a center frequency of 500 Hz and an ITD of 1500 μs. Four different values of IPD were used: 0 deg (squares), 90 deg (triangles), 180 deg (diamonds), and 270 deg (circles). The four panels represent data obtained from each of four listeners.

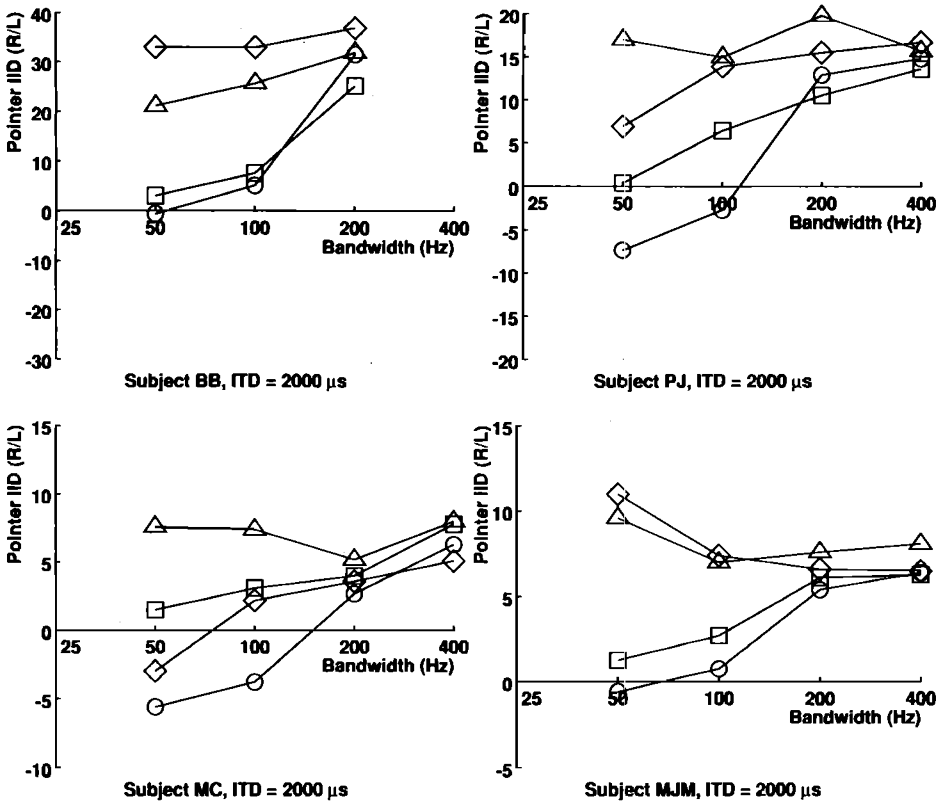

FIG. 5. Same as Fig. 4 with the exception that the ITD was 2000 μs.

creased. For the larger stimulus bandwidths, MC lateralized the targets far toward the right side of the head, consistent with the performance of the other listeners. For the record, we wish to note that individual matches of each of the listeners for the 50-Hz-wide targets revealed that they each heard the target consistently in a particular location of the head (i.e., they did not hear them first on one side of the head and then on another).

Stimuli presented with an ITD of 1500 μs and an IPD of 270 deg with extremely narrow bandwidths are similar to tonal stimuli that are presented with an IPD of 180 deg. This consideration alone would suggest that these targets would be equally likely to be heard on one side of the head or the other. It is possible that this ambiguity of the stimuli at low bandwidths may account for the differences between MC's matches and those of the other three listeners for stimuli with low bandwidths. On the other hand, the trajectory passing through $+1000\,\mu$s at 500 Hz is considerably straighter than the one that passes through $-1000\,\mu$s at that frequency. This factor would suggest that, as bandwidth increases, targets would be lateralized toward the right side of the head, as was seen for all listeners.

The data collected with an ITD of 2000 μs replicate some of the conditions originally considered by Jeffress (1972). Consistent with his analysis, all listeners reported that stimuli containing only the interaural delay of 2000 μs (and zero IPD) were lateralized near the center of the head when the bandwidth was small and moved increasingly toward the right as the bandwidth was increased. The rationale for these data is again indicated by the maxima of the cross-correlation functions in Fig. 3. Specifically, at 500 Hz, there is a trajectory precisely at the midline that would dominate the lateralization percept at extremely narrow bandwidths. As bandwidth increases, the image is expected to become dominated by the straight trajectory at τ equals 2000 μs (which corresponds to an image heard far to the right), as is indeed observed in the data of all listeners.

The stimuli presented with an IPD of 90 deg (in addition to the ITD of 2000 μs) were universally heard substantially toward the right by each listener, except for listener BB, who used increasingly greater amounts of pointer IID as bandwidth was increased to 200 Hz.[4] We believe that the narrow-band targets should be heard toward the right because the most central trajectory at 500 Hz is at approximately $+500\,\mu$s. As the bandwidth of the target is increased, the image would be expected to continue to be lateralized far toward the right, both because of the centrality of the trajectory mentioned above and because of the straightness of the adjacent trajectory that passes through $+2500\,\mu$s at 500 Hz. The additional contribution of the straightness of the adjacent trajectory is evident in the data of listener BB, who is the listener who appears to be the most sensitive to the relative straightness of the trajectories.

When the target was 50 Hz wide, data presented with an IPD of 180 deg vary considerably from listener to listener. BB and MJM indicated that they heard the target far to the right, while for PJ it appears that the target was perceived somewhat to the right. MC, on the other hand, apparently heard the target toward his left ear. This variability of matches from listener to listener probably occurs because the trajectories for these stimuli are symmetric about the midline at 500 Hz, producing a stimulus that is very similar to an interaurally out-of-phase tone. As the bandwidth increased to 400 Hz, all listeners (including MC) heard the targets far to the right. This probably occurs because, for broadband stimuli, the trajectory that passes through $+1000\ \mu s$ at 500 Hz is straighter than the trajectory at $-1000\ \mu s$.

Finally, 50-Hz-wide targets presented with an IPD of 270 deg (and an ITD of $2000\ \mu s$) were perceived either to the right (listeners MC and PJ) or near the midline (listeners BB and MJM). Again, as bandwidth increased to 400 Hz (or 200 Hz in the case of BB), targets were matched by IIDs indicating that they were heard far to the right. As before, the differences in response among the listeners probably occur because the trajectories depicting activity produced by these stimuli exhibit conflicting contributions of straightness and centrality. At narrow bandwidths, we expect that the targets would be lateralized toward the left side because of the most central trajectory that passes through $-500\ \mu s$ at 500 Hz. At broader bandwidths, however, the straighter trajectory that passes through $+1500\ \mu s$ at 500 Hz will become more dominant, causing the target to be heard on the right. Once more, the data conform to these expectations.

V. DISCUSSION

In general, the data from both experiments conform to our expectations and indicate that the intracranial position of acoustic images depends on the modes of the frequency-dependent cross-correlation function of the stimuli. Properties of the trajectories of such modes including their locations and relative straightness appear to mediate the perceived location of interaurally delayed and phase-shifted stimuli as a function of bandwidth.

Although the data of all listeners appear to reflect our expectations from the weighted-image model, it is clear, however, that there is great inter-listener variability in terms of the numerical values of the IIDs that were necessary to match the locations of the stimuli. Such variability has already been seen in the data of a number of similar experiments (e.g., Bernstein and Trahiotis, 1985a,b; Trahiotis and Bernstein, 1986). This variability can be attributed to at least two sources. First, the intracranial position of a stimulus presented with a particular IID is known to vary from listener to listener. Second, it appears that there are inter-listener differences in the relative weighting of straightness and centrality.

In order to examine the significance of the first effect in the present data, we utilized data that related the amount of IID of the pointer to the actual position in the head. Such data had been collected previously for each of the listeners. In those experiments, the listeners placed a mechanical slider at a position on a caricature of the human head to indicate where in *their* head they heard the pointer. IIDs were varied randomly and data were collected in 2-dB steps over a range of IIDs that was sufficient to span the locus of positions from one ear to the other. We then used these data to replot the results of the present experiments in terms of the positions of the mechanical slider (instead of the corresponding pointer IIDs). Essentially, this transformation allowed us to normalize the data in terms of perceived distances from midline to each ear. Because this transformation does not change any of the qualitative relations of the data discussed above, we will not present all of the experimental results in this manner. Instead, we show in Fig. 6 transformed data for the 1500-Hz stimuli of experiment II from the two subjects, BB and MJM, who represented the greatest differences in their overall use of pointed IIDs. Note that this transformation indicates that there are real individual differences not only in the pointer IID used by the subjects, but also in the extent of laterality produced by the stimuli.

Many recent discussions of the processing of complex and high-frequency binaural stimuli have focused on the relative salience of timing information that can be provided by the envelopes as compared to the fine structure of the stimulus. Some researchers discuss information obtained from the envelope in terms of group delay, or the local slope of the phase spectrum. (Variations of the fine structure can be discussed in terms of phase delay, which, at a given frequency, is equal to the IPD divided by the frequency.) It is reasonable, then, to think of the salience of timing information available in the envelopes of complex stimuli in terms of the extent to which group delay is consistent over a range of frequencies. If a particular stimulus has a group delay that is consistent over frequency, that group delay will correspond to an interaural phase difference that increases linearly with frequency. This, of course, is exactly the condition encountered if one has a stimulus with an ITD that is consistent over frequency, which produces a stimulus with at least one perfectly straight trajectory. In other words, those stimuli that produce trajectories which are straight in the τ-f plane are also exactly those stimuli that tend to exhibit envelopes with interaural timing information that can be used for localiza-

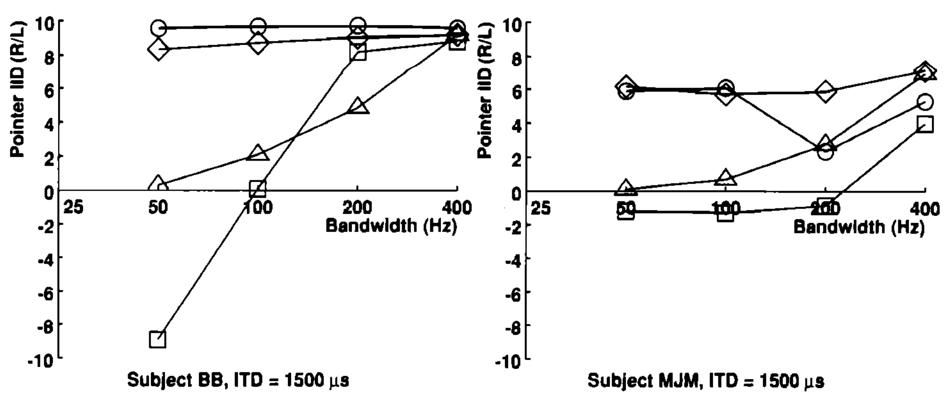

FIG. 6. Results of experiment II using 1500-μs ITDs that were replotted for selected listeners to describe the estimated perceived intracranial location of the stimuli for each subject. An experimentally derived monotonic function was used to convert the pointer IID into perceived lateral position (see text). Data are plotted for listeners BB and MJM.

tion. On the other hand, decreasing the straightness of the straightest trajectory by introducing a constant phase shift over all frequencies leaves the group delay unchanged. When such a physical manipulation produces a change in laterality, as seen in Figs. 4 and 5 of this study, then the intracranial location of the image cannot be based on the interaural delays of the envelope *per se*. Rather, such dependencies indicate that the locations of the images are mediated by competition between the attributes of envelope and fine-structure delay, or by the competition between the straightness of the trajectories of the cross-correlation function versus the centrality of the various modes in that function.

VI. SUMMARY AND CONCLUSIONS

The insights of Jeffress (1972) regarding how the lateral positions of complex stimuli can be joint functions of interaural delay and stimulus bandwidth were verified and extended. The lateral positions of sounds possessing interaural delays and/or interaural phase shifts were measured and were found to vary in accord with Jeffress's views. The data are consistent with a model that incorporates patterns of activity of the coincidence detectors which are assumed to interrelate activity over narrow-frequency regions stemming from each ear. The salient features of the patterns of activity are the centrality and straightness of the trajectories of the cross-correlation function, which are manifest as the coincident firing of neural units that possess characteristic internal delays.

The data appear to indicate clearly the utility of considering the role played by bandwidth in a comprehensive model of binaural hearing. In addition, the data clearly reveal individual differences in the potency of interaural cues as measured by extent of lateral position. Such individual differences appear to be indicative of the relative import of straightness and centrality and do not appear to require the postulation of other variables. Overall, the data and the theoretical notions that stimulated these empirical investigations appear to lend credence to modern cross-correlation-based models of binaural hearing. Interestingly, manipulations of the stimuli that produce straightness of neural activity within the model are those that produce consistent delays in the envelopes of the stimuli.

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[1]We use the definition of cross correlation in Eq. (1) rather than the more common

$$R_s(\tau) = E[s_L(t)s_R(t+\tau)] = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} s_L(t)s_R(t+\tau)dt$$

to facilitate more intuitive comparisons between theoretical predictions and the experimental data to be described. With the definition used in this paper, a broadband stimulus with a small positive ITD will generally be lateralized toward the right side of the head. Such a stimulus will exhibit a set of trajectories of modes of the cross-correlation function in which the most central trajectory will appear on the right side of the f-τ plane.

[2]We report the pointer position in terms of dB (R/L), instead of dB (L/R) as in previous papers (e.g., Bernstein and Trahiotis, 1985a,b; Trahiotis and Bernstein, 1986). This convention was also adopted to facilitate more intuitive comparisons between predictions and data. Using this convention, a stimulus presented with a positive IID will be perceived toward the same side of the head as the perceived image of a stimulus presented with a small positive ITD. The data were actually collected in terms of dB (L/R), such that a positive IID indicated that a stimulus presented with the more intense signal to the left ear, and a positive ITD indicated that a stimulus was presented with the signal to the left ear leading in time. Our reversal of notational conventions should have no substantitive effect on the interpretation of the data and predictions because the binaural system has always been found to be left–right symmetric in similar experiments.

[3]One of the reviewers asked whether the stimuli that produced *straight* trajectories of the peaks of the cross-correlation function were more compact, and, conversely, whether stimuli for which all cross-correlation peaks fell along a curve produced images that had relatively large intracranial extent. The listeners who had participated in the experiments were not asked and did not voluntarily remark about the relative compactness of the images. Prior to experimentation, however, author CT listened to virtually all of the stimuli and does not remember noting any such effects. In addition, prompted by the reviewer's question, author CT listened once again to many of the signals, as did his two well-practiced colleagues, Dr. Les Bernstein and Dr. Thomas Buell. All three agreed that there were no obvious or compelling changes in compactness for such stimuli.

[4]No data were collected from listener BB with an ITD of 2000 μs and a bandwidth of 400 Hz because she became unavailable before testing was completed. Fortunately, all of the data collected with a bandwidth of 200 Hz indicate images that are clearly lateralized far toward the right side of the head. From all the data presented thus far and from theoretical considerations, we believe that BB's data at 400 Hz would also have been far toward the right side of the head.

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