Enhancing sensitivity to interaural delays at high frequencies by using "transposed stimuli"[a)]

Leslie R. Bernstein
Department of Neuroscience, University of Connecticut Health Center, Farmington, Connecticut 06030

Constantine Trahiotis
Department of Neuroscience and Department of Surgery (Otolaryngology), University of Connecticut Health Center, Farmington, Connecticut 06030

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It is well-known that thresholds for ongoing interaural temporal disparities (ITDs) at high frequencies are larger than threshold ITDs obtained at low frequencies. These differences could reflect true differences in the binaural mechanisms that mediate performance. Alternatively, as suggested by Colburn and Esquissaud [J. Acoust. Soc. Am. Suppl. 1 **59**, S23 (1976)], they could reflect differences in the peripheral processing of the stimuli. In order to investigate this issue, threshold ITDs were measured using three types of stimuli: (1) low-frequency pure tones; (2) 100% sinusoidally amplitude-modulated (SAM) high-frequency tones, and (3) special, ''transposed'' high-frequency stimuli whose envelopes were designed to provide the high-frequency channels with information similar to that available in low-frequency channels. The data and their interpretation can be characterized by two general statements. First, threshold ITDs obtained with the transposed stimuli were generally smaller than those obtained with SAM tones and, at modulation frequencies of 128 and 64 Hz, were equal to or smaller than threshold ITDs obtained with their low-frequency pure-tone counterparts. Second, quantitative analyses revealed that the data could be well accounted for via a model based on normalized interaural correlations computed subsequent to known stages of peripheral auditory processing augmented by low-pass filtering of the envelopes within the high-frequency channels of each ear. The data and the results of the quantitative analyses appear to be consistent with the general ideas comprising Colburn and Esquissaud's hypothesis. [DOI: 10.1121/1.1497620]

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I. INTRODUCTION

The ability to discriminate changes in ongoing interaural temporal disparities (ITDs) can be much poorer when the information is conveyed by high-frequency stimuli, as compared to when it is conveyed by low-frequency stimuli (e.g., Klumpp and Eady, 1956; Zwislocki and Feldman, 1956; McFadden and Pasanen, 1976; Nuetzel and Hafter, 1976; Henning, 1980; Bernstein and Trahiotis, 1982, 1994; Blauert, 1983). In addition, and logically consistent with those results, it has been found that functions relating extent of laterality to ITD measured with high-frequency stimuli are typically more shallow than those measured with low-frequency stimuli. That is, for a given ITD, intracranial images produced by high-frequency stimuli are perceived to be much closer to the midline than are intracranial images produced by low-frequency stimuli. (e.g., Blauert, 1982; Bernstein and Trahiotis, 1985).

One logical possibility is that these differences in the relative potency of ITDs result primarily from differences between the (central) *binaural* mechanisms that mediate interaural interactions in low- and high-frequency regions, respectively. Another possibility is that the observations reflect inherent frequency-related differences in the neural information that serves as input to the binaural portion of the auditory system. This latter possibility was favored by Colburn and Esquissaud (1976). They suggested that frequency-related differences in sensitivity to ongoing ITDs could result from the rectification and low-pass filtering that occurs as a natural part of monaural, peripheral processing. For low-frequency stimuli, such processing would result in neural impulses synchronized to the whole *waveform* (i.e., both the fine-structure *and* the envelope). For high-frequency stimuli, such processing would result in neural impulses synchronized to only the *envelope* of the waveform. An important assumption made by Colburn and Esquissaud was that the binaural (cross-correlation) mechanism that receives the two types of synchronized neural impulses operates uniformly across frequency.

We recently published data and analyses that we believe strongly support Colburn and Esquissaud's (1976) contention that the binaural comparator functions uniformly across frequency (Bernstein and Trahiotis, 1996b). Utilizing a NoSo vs NoSπ discrimination task, we found that binaural detection measured as a function of the center frequency of the stimuli could be accounted for by utilizing normalized interaural correlations computed subsequent to rectification and low-pass filtering. This type of model provides, as a function of frequency, the types of inputs Colburn and Esquissaud postulated would naturally occur for binaural comparison.

The purpose of this paper is to report the results of new

[a)]A portion of this work was presented at the 141st meeting of the Acoustical Society of America, 2001, Chicago, Illinois.

experiments that lend additional general support to Colburn and Esquissaud's (1976) thesis. The experiments were designed with the goal of providing the high-frequency channels of the binaural processor with envelope-based inputs that, other things being equal, would essentially mimic waveform-based inputs normally available in the low-frequency channels. Such stimuli were generated by capitalizing on the "transposition" technique described by van de Par and Kohlrausch (1997).

We measured sensitivity to changes in ITDs for high-frequency "transposed" stimuli and compared those thresholds to thresholds measured with low-frequency tones and to thresholds measured with high-frequency tones that were sinusoidally amplitude-modulated (SAM). It will be seen that the high-frequency "transposed" stimuli yielded threshold ITDs that were substantially smaller than those obtained with high-frequency SAM tones and which, for low rates of modulation, were as small or smaller than threshold ITDs measured with low-frequency pure tones. In addition, it will be seen that the data can be accounted for via normalized interaural correlations computed subsequent to transformations that reflect known stages of peripheral auditory processing with the proviso that the envelopes within the high-frequency channels are subjected to low-pass filtering at 150 Hz. The data and their analysis appear to be consistent with Colburn and Esquissaud's (1976) general idea that differences in the inputs to the binaural processor between the low-frequency and high-frequency portions of the auditory system are primary determiners of sensitivity to ITD.

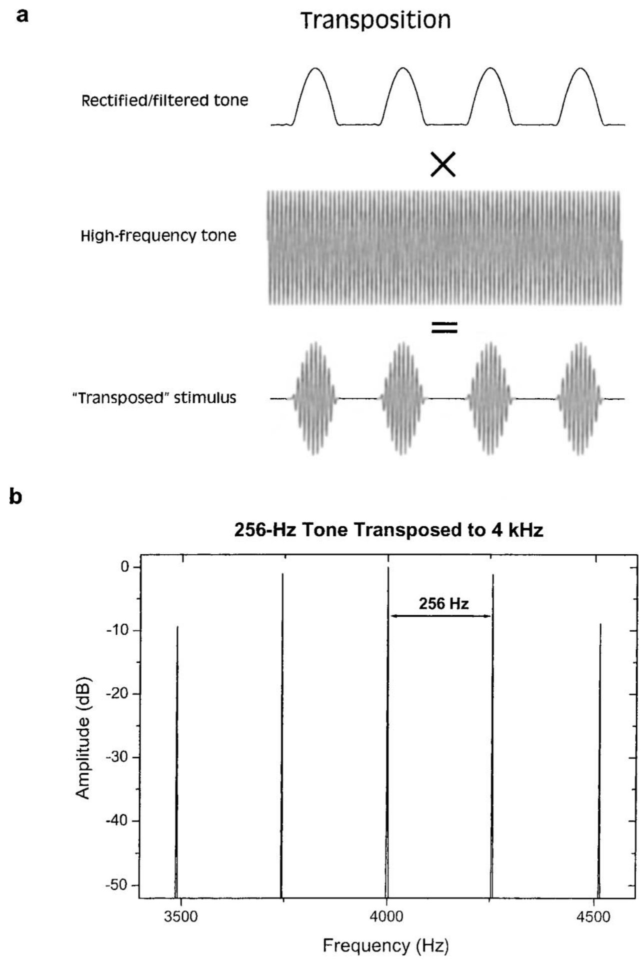


FIG. 1. Panel (a) Schematic representation of the method used to generate transposed stimuli. Panel (b) Power spectrum of a 256-Hz tone transposed to 4 kHz (see the text).

II. EXPERIMENT 1

A. Stimulus generation

Low-frequency sinusoids and high-frequency SAM tones were generated digitally in the frequency domain. The high-frequency transposed stimuli were generated employing a technique similar to that described by van der Par and Kohlrausch (1997). The general technique is illustrated in Fig. 1(a). First, the time-domain representation of a low-frequency waveform was (linearly) half-wave rectified by setting all negative values to zero. The rectified waveform was then transformed to the frequency domain and the magnitudes of components above 2 kHz were filtered out by setting them to zero. Then, the signal that resulted was transformed back to the time domain (top row) and multiplied by a high-frequency sinusoidal carrier having the desired center frequency of the transposed stimulus (middle row). The final product (bottom row) was the transposed stimulus having an envelope whose time signature mimicked that of the rectified and filtered pure tone.

Figure 1(b) displays the power spectrum of one of the transposed stimuli used in the experiment. In this case, a pure tone having a frequency of 256 Hz was transposed to 4 kHz. Like all of the transposed stimuli employed, the spectral components are symmetric and limited to ± 2 kHz around the center frequency. For this example, the technique results in the presence of sidebands at 4000 ± 256, ± 512, ± 1024, and ± 1536 Hz. Were no rectification applied to the 256-Hz tone, only the two sidebands at 4000 ± 256 Hz would be present.

It is important to understand why linear half-wave rectification followed by spectral limiting at 2 kHz was employed. A high-frequency transposed stimulus would, like any other signal, be subjected to *internal* rectification and low-pass filtering by the listener's auditory system. As a result, the internal representation of the transposed stimulus would be expected to reflect the sequential effects of the external and (perhaps, nonlinear) internal rectification and the sequential effects of external and internal low-pass filtering. Linear rectification and low-pass filtering at 2 kHz was employed because their effects would be essentially transparent when followed by internal (linear or nonlinear) rectification and the internal low-pass filtering that characterizes the neural synchrony to stimulus waveforms. This argument implicitly assumes (1) that the "rectification" that occurs in the peripheral auditory system removes all, or essentially all, of the negative portions of the external waveform and (2) that the cutoff of the internal low-pass filtering is substantially below 2 kHz. Numerous physiological data and analyses appear to support both assumptions (e.g., Rose *et al.*, 1967; Brugge *et al.*, 1969; Johnson, 1980; Palmer and Russell, 1986).

There are two other lines of evidence that attest to the

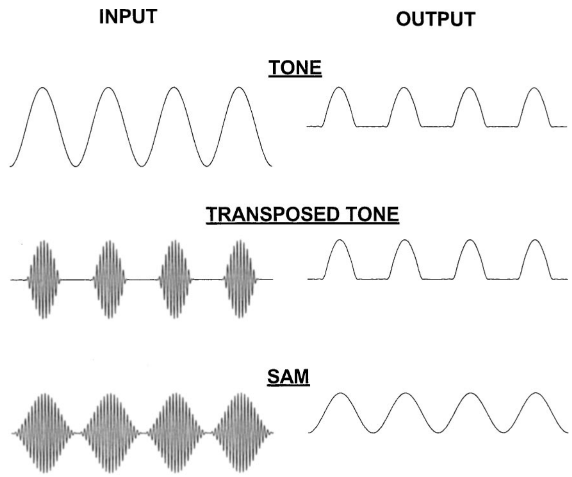


FIG. 2. Left side: A 250-Hz tone (upper), a 250-Hz tone transposed to 4 kHz (middle), and a 4-kHz tone sinusoidally amplitude modulated at 250 Hz (lower). Right side: The same three stimuli subsequent to bandpass filtering, rectification, and low-pass filtering.

suitability of the overall procedure. First, considering the stimuli themselves, we verified via computer simulations that employing a low-pass cutoff of 2 kHz had negligible effects on the envelopes of the transposed stimuli in that those envelopes differed minimally from the half-wave rectified tones used to generate them. Thus, it appears that the procedure yields physical stimuli, *per se*, that fulfill our requirements. Second, van de Par and Kohlrausch (1997) have recently shown that restricting the spectra of transposed stimuli in a similar manner such that only three or five central components remain did not adversely affect improvements in binaural detection thresholds.

B. Procedure

Detection of ongoing ITD was measured using three types of stimuli: (1) low-frequency pure tones; (2) low-frequency tones transposed to 4 kHz; (3) 100% sinusoidally amplitude-modulated (SAM) tones centered at 4 kHz. The frequencies of the pure tones and the rates of modulation of the SAM and transposed stimuli were either 32, 64, 128, 256, or 512 Hz.

Figure 2 provides an illustration of the idealized case for three types of stimulus waveforms when the frequency of the pure tone and the frequency of modulation were each 250 Hz. The waveforms are shown both at the input and at the output of putative peripheral processing (rectification and low-pass filtering that results in extraction of the envelope at high frequencies).

The figure illustrates that, for the low-frequency 250-Hz tone (top row), the effect of peripheral processing is to pass only the positive values of the waveform. That is, the waveform has been half-wave rectified. For the transposed stimulus (middle row) and for the SAM tone (bottom row), the effect of peripheral processing is to extract the envelope of the waveform. The fine-structure at 4000 Hz is removed because low-pass filtering smooths over oscillations at this frequency. Note that the pure tone (top row) and the transposed stimulus (middle row) result in output waveforms that are essentially identical half-wave rectified sinusoids. For these two stimuli, peripheral processing results in outputs characterized by distinct ''off'' regions between the ''peaks'' during which the waveform remains at or close to a value of zero. In contrast, note that the corresponding output for the SAM tone (bottom row) is an unrectified sinusoid and has no such distinct ''off'' regions. It seems reasonable to assume that period histograms of neural discharges created by the transduction of low-frequency tones and transposed tones would be relatively less dispersed in time (have a smaller variance) than period histograms for SAM tones.

To the degree that such greater neural synchrony results in smaller threshold ITDs, one would expect that, for a given pure tone or modulation frequency, threshold ITDs obtained with a high-frequency transposed stimulus would be smaller than those obtained with its high-frequency SAM tone counterpart and, ideally, be equivalent to the threshold ITDs obtained with the low-frequency pure tone. The word ''ideally'' is used because close correspondence between the outputs in low-frequency and high-frequency regions and between their respective neural inputs to the binaural processor may not always be expected to occur within the auditory system. Exceptions could occur that stem from the effects of peripheral bandpass filtering and from a ''rate limitation'' that degrades the processing of high rates of fluctuation of the envelopes of high-frequency stimuli. Both of these factors will be discussed in context when the data are presented. To the degree that these two factors play a role, one would not expect threshold ITDs obtained with transposed stimuli to be as small as those obtained with their low-frequency pure-tone counterparts.

All three types of stimuli were generated digitally with a sampling rate of 20 kHz (TDT AP2), were low-pass filtered at 8.5 kHz (TDT FLT2), and were presented via Etymotic ER-2 insert earphones at a level matching 75 dB SPL as produced by TDH-39 earphones in a 6-cc coupler.[1] The duration of each stimulus was 300 ms including 20-ms $\cos^2$ rise–decay ramps. For the high-frequency stimuli, a continuous diotic noise low-pass filtered at 1300 Hz (No equivalent to 30 dB SPL) was presented to preclude the listeners' use of any information at low spectral frequencies (e.g., Nuetzel and Hafter, 1976, 1981; Bernstein and Trahiotis, 1994).

Threshold ITDs were determined using a two-cue, two-alternative, forced choice, adaptive task. Each trial consisted of a warning interval (500 ms) and four 300-ms observation intervals separated by 400 ms. Each interval was marked visually by a computer monitor. Feedback was provided for approximately 400 ms after the listener responded. The stimuli in the first and fourth intervals were diotic. The listener's task was to detect the presence of an ITD (left-ear leading) that was presented with equal *a priori* probability in either the second or the third interval. The remaining interval, like the first and fourth intervals, contained diotic stimuli.

For the low-frequency tones and the high-frequency SAM stimuli, the starting phase of the components comprising each stimulus (prior to the imposition of an ITD) was chosen randomly for each observation interval within and across trials. All of the waveforms required for a given trial were computed immediately prior to that trial. Because of the time required to generate the high-frequency transposed stimuli, it was necessary to calculate the transposed waveforms prior to each adaptive run. Twenty independently calculated tokens of the desired type of transposed stimulus were stored and one of them was chosen, with replacement, for each observation interval within each trial. Twenty tokens were used to ensure that the results were not dependent upon any particular stimulus. This number of tokens was considered to be sufficiently large based on Siegel and Colburn's (1989) findings that only ten independently generated tokens of noise yielded essentially equivalent performance to that measured with ''running'' noise in a binaural discrimination task.

For all three types of stimuli, ongoing ITDs were imposed by applying linear phase shifts to the representation of the signals in the frequency domain and then gating the signals destined for the left and right ears coincidentally, after transformation to the time domain. The ITD for a particular trial was determined adaptively in order to estimate 70.7% correct (Levitt, 1971). The initial step size for the adaptive track corresponded to a factor of 1.584 (equivalent to a 2-dB change of ITD) and was reduced to a factor of 1.122 (equivalent to a 0.5-dB change of ITD) after two reversals. A run was terminated after 12 reversals and threshold was defined as the geometric mean of the ITD across the last ten reversals.

Four normal-hearing adults served as listeners and three consecutive thresholds were first obtained from each listener for each of the particular stimulus conditions (type of stimulus$\times$frequency), which were chosen in random order. Then, three more thresholds were obtained by revisiting the same stimulus conditions in reverse order. The same ordering of conditions was used for all listeners and all listeners received substantial practice before formal collection of data began. For each listener and stimulus condition, final estimates of thresholds were calculated by averaging the individual thresholds obtained from six adaptive runs.

C. Results and discussion

Figure 3 displays the mean threshold ITDs computed across the four listeners for the three types of stimuli. The thresholds are plotted as a function of either the frequency of the pure tone or the frequency of modulation of the high-frequency SAM and transposed stimuli. When we refer to the frequency of modulation of a transposed stimulus, we refer to the frequency of the pure tone that was used to generate it. The parameter within the plot is the type of stimulus that conveyed the ITD, and the error bars represent ± 1 standard error of the mean. Note that, as signified by the ''broken'' ordinate and ''broken'' lines through the data, no values of threshold ITD are plotted for SAM and transposed stimuli having rates of modulation of 512 Hz. This is so because, for two of the listeners, thresholds ITDs could not be determined even with ITDs of up to 1 ms. Therefore, no valid mean threshold ITD could be calculated.

Beginning with the SAM tones (squares), Fig. 3 indicates that threshold ITDs are in the range of 130 to 260 μs and are smallest for the intermediate frequencies of modulation. These values of threshold ITD are consistent with those

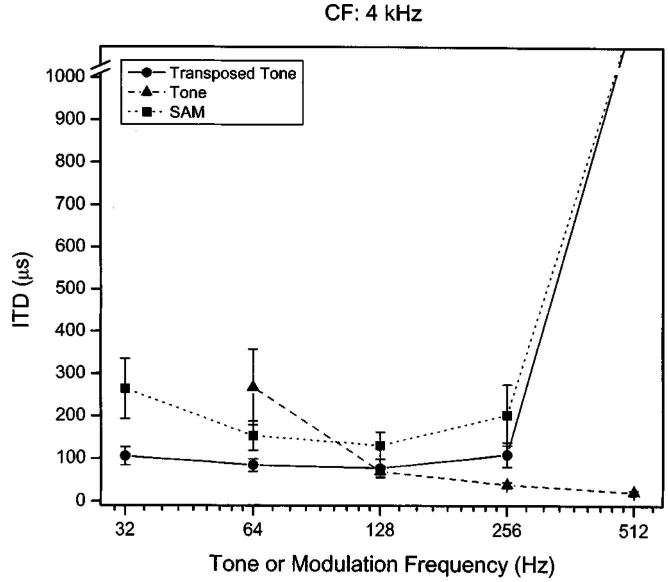


FIG. 3. Threshold ITDs averaged across the four listeners as a function of the modulation or pure-tone frequency. The center frequency of the high-frequency SAM and transposed stimuli was 4 kHz. The parameter of the plot is the type of stimulus employed. The error bars represent $\pm$ standard error of the mean. The ''broken'' ordinate and ''broken'' lines through the data indicate conditions for which average threshold ITDs could not be computed because, for a subset of the listeners, thresholds could not be determined even for ITDs of up to 1 ms.

obtained in earlier investigations with similar stimuli (e.g., Henning, 1974; Nuetzel and Hafter, 1981; Bernstein and Trahiotis, 1994)[2] and, therefore, provide a valid basis for comparison. Threshold ITDs obtained with the transposed stimuli (circles) are consistently and substantially smaller than those obtained with the SAM tones (squares). This outcome is in line with our arguments concerning the peripheral processing of the stimuli. Specifically, the threshold ITDs measured with the transposed stimuli are roughly half those measured with the SAM stimuli.

The threshold ITDs obtained with the pure tones at 128, 256, and 512 Hz (triangles) are very similar to those obtained in previous studies (e.g., Klumpp and Eady, 1956; Zwislocki and Feldman, 1956). In addition, as observed in those studies, threshold ITDs declined as frequency was increased toward 512 Hz. The relatively large mean threshold ITD of 268 μs and relatively large standard error of 89 μs at 64 Hz occurred because the threshold obtained from one of the listeners (JB) was much larger (533 μs) than those obtained from the other three listeners. Calculating the mean threshold after excluding JB's data reduced the mean threshold ITD at 64 Hz to 180 μs and the standard error to 17μs. Those values are in line with those obtained at the higher tonal frequencies.

In an effort to determine whether JB's relatively high threshold resulted from the relatively lower sensation level of the 64-Hz tone, as compared to the higher frequency tones that were presented at the same sound-pressure level, additional measures of threshold were obtained after increasing the level of the 64-Hz tone by 10 dB. This reduced JB's threshold ITD to 163 μs while having very little, if any, effect on the threshold ITDs obtained from the other three listeners. On the basis of these findings, we consider the recalculated threshold of 180μs as being more indicative of the average listener's ability to resolve ITDs at 64 Hz.

Comparisons among threshold ITDs obtained with low-frequency pure tones (triangles) and their transposed counterparts (circles) indicate that sensitivity to ITD in high-frequency channels of the auditory system can, for stimuli having low rates of modulation, be as good as or even better than that measured in low-frequency channels. Specifically, at 128 Hz, threshold ITDs for transposed and tonal stimuli are essentially equivalent, being 76 and 69 μs, respectively. At 64 Hz, the threshold ITD obtained with the transposed stimulus (95 μs) is actually *smaller* than that obtained with the pure tone, independent of whether one uses the plotted mean threshold ITD (268 μs) or the recalculated mean (180 μs) to represent threshold for the pure-tone condition.

The data obtained at higher rates of modulation, 256 and 512 Hz, however, indicate that threshold ITDs obtained with transposed stimuli are larger than their pure-tone counterparts. The mean threshold ITD obtained with the pure tone of 256 Hz is smaller than that obtained with the transposed stimulus and, while listeners were quite sensitive to ITDs conveyed by a pure tone of 512 Hz, they were quite insensitive to ITDs conveyed by its transposed counterpart. For two different reasons, this outcome was not surprising. First, both SAM tones and transposed stimuli contain "sidebands" that would be subjected to increasing amounts of attenuation via peripheral filtering as the rate of modulation (and thus the separation in frequency between the sidebands) is increased such that the sidebands fall within the "skirt" of the filter. Nuetzel and Hafter (1981) specifically discussed how peripheral filtering would lead to attenuation of the sidebands of SAM tones and how that attenuation would result in reductions in depth of modulation which, in turn, could lead to degradations in sensitivity to ITD. Bernstein and Trahiotis (1996a) showed how reductions in depth of modulation result in poorer ITD thresholds by considering how changes in depth of modulation affect the normalized interaural correlation. More recently, van der Par and Kohlrausch (1997) also considered how peripheral attenuation of the sidebands of high-frequency transposed stimuli could degrade binaural detection in an MLD task.

The second reason this outcome was expected is that there appears to exist a limitation in the ability of the auditory system to follow rates of fluctuation of the envelope that are greater than about 150 Hz. Data supporting the existence of such a limitation have been reported in several binaural investigations (e.g., McFadden and Pasanen, 1976; Bernstein and Trahiotis, 1992a, 1992b, 1994) and, as discussed in the latter three of those studies, the process limiting the ability to follow rapidly changing envelopes appears to operate independently of peripheral bandpass filtering. It is interesting, historically, that Nuetzel and Hafter (1981), who favored an explanation based solely on peripheral filtering, acknowledged the logical possibility that such a rate limitation could have affected the ITD thresholds they measured using high-frequency SAM tones.

Additional empirical evidence that an envelope rate limitation is manifest at high spectral frequencies has been provided by Kohlrausch *et al.* (2000) and Ewert and Dau (2000). In both of those studies, temporal modulation transfer functions (TMTFs) were measured at various center frequencies. The patterning of the data and their quantitative analyses led them to include a low-pass filter in their model that serves to attenuate, independent of the center frequency of the stimulus, fluctuations of the envelope that are more rapid than 150 Hz. The common inferences from these studies and from a more recent study by Moore and Glasberg (2001) are that (1) there appears to be a monaural process that functionally acts as a low-pass filter on the envelope-based information that serves as input to more central stages of processing and (2) the low-pass filtering of the envelope appears to be functionally independent of the center frequency of the stimuli and, by necessity, independent of the width of initial peripheral bandpass filtering.

In summary, threshold ITDs obtained with high-frequency transposed stimuli: (1) are consistently smaller than those obtained with high-frequency SAM tones and (2) at frequencies of modulation of 128 and 64 Hz, are as small or smaller than threshold ITDs obtained with low-frequency pure tones. In our view, these findings are consistent with Colburn and Esquissaud's (1976) general hypothesis that transformations affecting the inputs to the binaural processor are responsible for the finding that threshold ITDs obtained at high frequencies are typically larger than those obtained at low frequencies.

The reader is reminded that two of the four listeners were essentially unable to perform the task with SAM and transposed stimuli having a rate of modulation of 512 Hz. This outcome motivated us to determine whether there were consistent inter-individual differences in relative sensitivity to ITD across the frequencies of modulation tested. In order to do so, the data from each listener were normalized by dividing the threshold ITD in each condition by the listener's threshold ITD measured with the SAM tone having a rate of modulation of 128 Hz. That stimulus was chosen as the "standard" for comparison because rates of modulation close to that frequency have been shown in several studies to yield relatively small threshold ITDs (e.g., Henning, 1974; Nuetzel and Hafter, 1981; Bernstein and Trahiotis, 1994). Normalizing the data in this manner permits one to make useful comparisons of relative performance within and across individual listeners, even when there are differences in the types of stimuli employed and in absolute sensitivity to ITD.

Figure 4 contains the normalized thresholds for data obtained with the SAM tones and the transposed stimuli plotted as bar graphs. The data are grouped by modulation frequency so that within- and across-listener trends in the data can be easily discerned. The horizontal dotted line at a value of 1.0 represents, for each listener, the threshold ITD obtained with the 128-Hz SAM reference stimulus. For all listeners, for rates of modulation below 512 Hz, threshold ITDs obtained with the transposed stimuli (filled bars) are smaller than those obtained with the SAM tone (unfilled bars). The only exception occurred for our most sensitive listener, AC, at a frequency of modulation of 256 Hz. Her un-normalized threshold ITDs for the SAM and transposed stimuli were 70 and 77 μs, respectively, indicating excellent sensitivity to

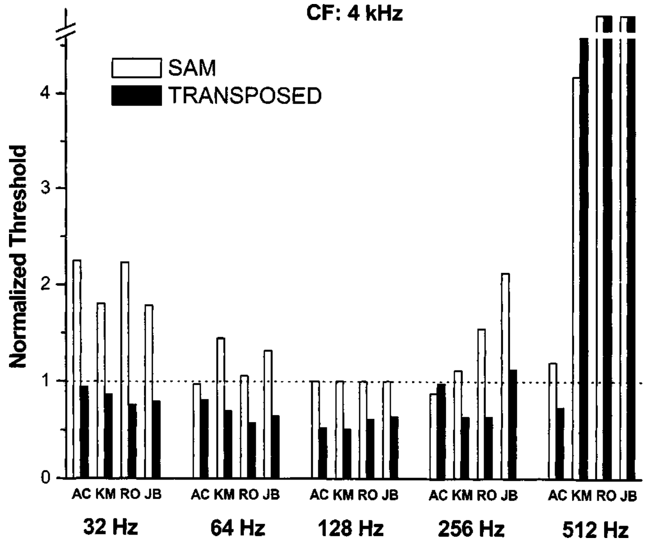


FIG. 4. Normalized threshold ITDs for the SAM (open bars) and transposed stimuli (filled bars) centered at 4 kHz. The data from each listener were normalized by dividing the threshold ITD in each condition by the listener's threshold ITD measured with the SAM tone having a rate of modulation of 128 Hz. The data for the four individual listeners are grouped by modulation frequency. The broken ordinate and broken bars indicate conditions in which thresholds could not be determined even for ITDs as large as 1 ms.

ITDs conveyed by both types of stimuli. The patterning of the normalized data clearly indicates that for both SAM tones and transposed stimuli there were essentially no inter-individual differences in relative sensitivity to ITD for rates of modulation of 32, 64, and to 128 Hz. In contrast, at 256 Hz, the heights of the bars reflect moderate inter-individual differences and at 512 Hz, there are large inter-individual differences. At the latter frequency, one of the listeners (AC) performed as well as for the lower rates, one of the listeners (KM) required approximately four to five times the ITD required at 128 Hz, and two of the listeners (RO and JB) could not perform the task given repeated attempts with ITDs of up to 1 ms.

Our interpretation of the relations among the data in Fig. 4 is that the data obtained from each individual confirm the representative nature of the averaged threshold ITDs depicted in Fig. 3. In addition, we believe that the inter-individual differences that did occur most likely did not stem from inter-individual differences in the ability to process ITDs, *per se*.

III. EXPERIMENT 2

Following the collection of data with stimuli centered at 4 kHz, data were obtained with SAM tones and transposed stimuli centered at either 6 or 10 kHz in order to assess the generalizability of the findings. At the higher frequencies, the widths of the peripheral filters are greater than at 4 kHz, and any reduction in the depth of modulation that occurred at 4 kHz would be expected to be less severe or absent at 6 and 10 kHz. Therefore, to the degree that reductions of the depth of modulation were responsible for loss of sensitivity to ITD for high rates of modulation at 4 kHz, one would expect performance to be *improved* by increasing the center frequency to 6 or 10 kHz. On the other hand, recent experiments have indicated that sensitivity to ITDs conveyed by the envelopes of conventional high-frequency stimuli (e.g., SAM tones) having center frequencies higher than 4 kHz can be much *poorer* than that observed at 4 kHz. (e.g., Henning, 1974; Bernstein and Trahiotis, 1994). A similar finding with transposed stimuli could indicate that sensitivity to ITD, *per se*, decreases at the higher frequencies as a result of unknown factors probably not associated with the peripheral processing of the stimuli.

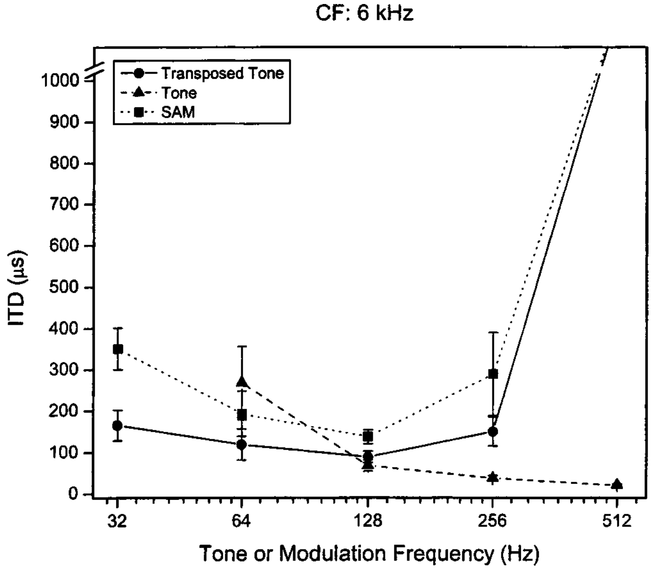
The procedures used to obtain threshold ITDs at 6 and 10 kHz were the same as those described for experiment 1, save for the fact that the stimuli were generated with a suitably higher sampling rate (27.056 kHz) and an increased cutoff frequency of the low-pass, anti-imaging filter (12.75 kHz). The listeners were the four who participated in experiment 1. All of the data with stimuli centered at 6 kHz were collected prior to collecting the data with stimuli centered at 10 kHz. It was judged that ''blocking'' the conditions in this manner would give the listeners the greatest opportunity to achieve their best performance in what was expected to be a difficult task.

A. Results and discussion

The top and bottom panels of Fig. 5 display the mean threshold ITDs for the stimuli centered at 6 and 10 kHz, respectively. The threshold ITDs obtained with pure tones are replotted from Fig. 1. The thresholds obtained at 6 kHz are slightly, but consistently, larger than those obtained at 4 kHz and the overall patterning of the data at the two center frequencies is virtually identical. Once again, the threshold ITDs obtained with the transposed stimuli are smaller than those obtained with the SAM tones. Note that, as was the case at 4 kHz, the threshold ITD obtained with the transposed stimulus having a rate of modulation of 128 Hz is, for practical purposes, equivalent to that obtained with a 128-Hz pure tone, and the one obtained with a rate of modulation of 64 Hz is smaller than that obtained with its pure-tone counterpart.

The data obtained at 10 kHz are somewhat different in that threshold ITDs are generally larger, being, when measurable, two to three times those obtained at 4 kHz. As indicated in the figure, mean threshold ITDs could not be computed at 256 and 512 Hz. This occurred because some listeners could not perform the task at these rates of modulation even with ITDs as large as 1 ms. A comparable loss of sensitivity to ITD at very high center frequencies (8 and 12 kHz) was reported by Bernstein and Trahiotis (1994).

The differences in threshold ITDs obtained with transposed stimuli and the SAM tones having rates of modulation of 32, 64, and 128 Hz are even larger than those found at 4 and 6 kHz. This stems largely from the fact that the threshold ITDs obtained with both SAM tones and the transposed stimuli, in general, doubled when center frequency was increased to 10 kHz. Thus, when the differences in threshold ITDs between SAM and transposed stimuli are considered in terms of ratios, it appears that about the same relative improvement occurs with transposed stimuli, independent of center frequency. Perhaps the biggest departure in the patterning of the data at 10 kHz is that mean threshold ITDs



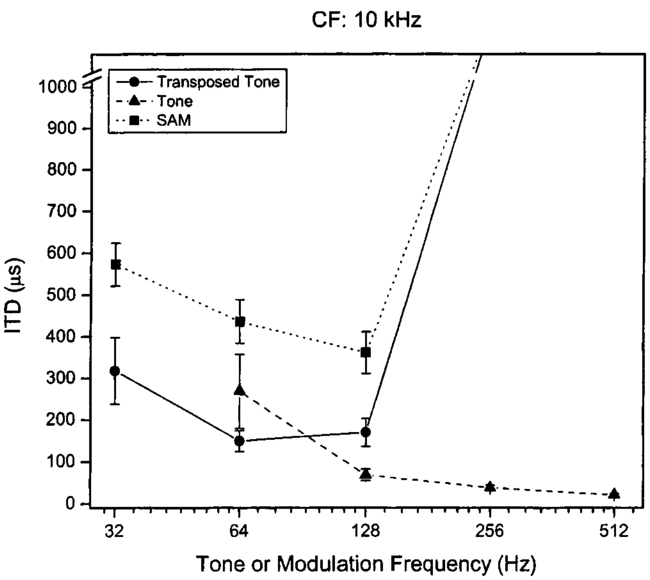
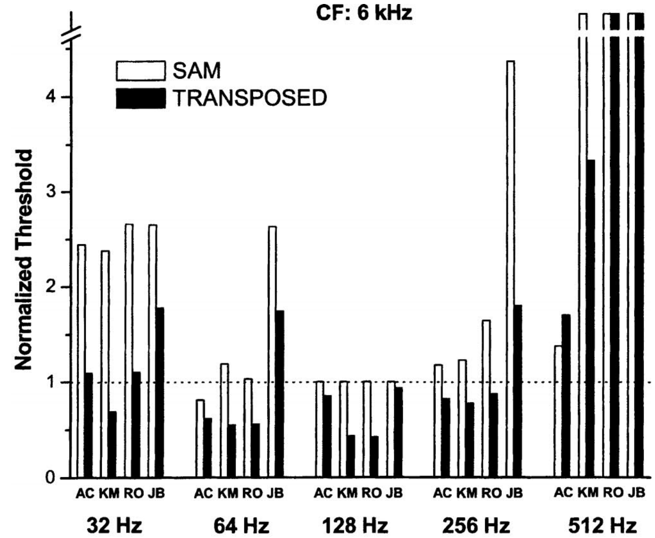


FIG. 5. Same as Fig. 3, but for SAM and transposed stimuli centered at 6 kHz (upper panel) and 10 kHz (lower panel).



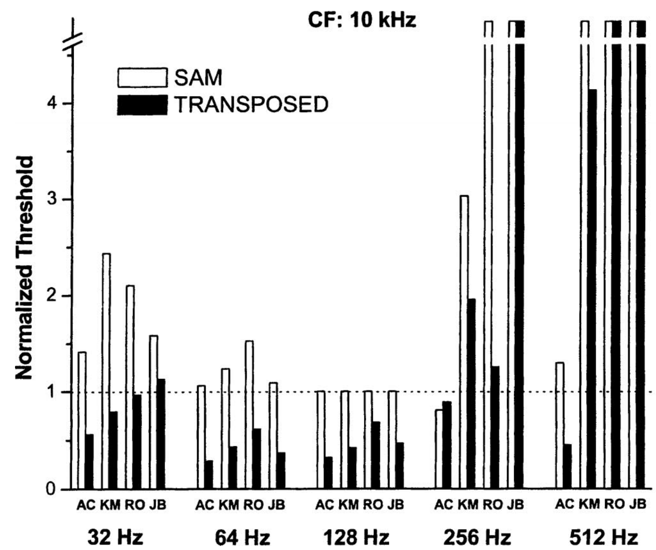


FIG. 6. Same as Fig. 4, but for SAM and transposed stimuli centered at 6 kHz (upper panel) and 10 kHz (lower panel).

could not be computed for data obtained at a rate of modulation of 256 Hz. This was so because two of the listeners, RO and JB, were unable to perform the task with either SAM or transposed stimuli.

The top and bottom panels of Fig. 6 contain individual listener's normalized thresholds at 6 and 10 kHz, respectively. At 6 kHz, the threshold ITDs obtained from all four listeners with the transposed stimuli (filled bars) were, once again, smaller than those obtained with the SAM tones (unfilled bars). The patterning of the normalized data at 6 kHz is very much like that found at 4 kHz with the exception that listener JB's normalized thresholds for rates of modulation of 64 and 256 Hz were larger than they were at 4 kHz. Still, listener JB's data clearly indicate smaller threshold ITDs with transposed stimuli than with SAM tones. The picture is much the same at 10 kHz, save for the fact that threshold ITDs were unmeasurable for listeners RO and JB in conditions in which the rate of modulation was 256 Hz. It is interesting, and to us important, that Fig. 6 reveals three stimulus conditions (a rate of modulation of 512 Hz for stimuli centered at 6 kHz, and rates of modulation of 256 and 512 Hz for stimuli centered at 10 kHz) in which listener KM was unable to perform the task with a SAM tone but was able to perform the task with a transposed stimulus.

The data obtained at center frequencies of 6 and 10 kHz, like those obtained at 4 kHz, indicate that threshold ITDs obtained with transposed stimuli are smaller than those obtained with SAM tones, and can sometimes lead to threshold ITDs that are essentially equivalent to or smaller than those obtained with low-frequency pure tones. Therefore, it appears to be generally true that the relative insensitivity to ITD typically observed with conventional high-frequency stimuli primarily stems from the nature of the information at the input to the binaural processor. That is, the high-frequency channels can support excellent sensitivity to ITD when the "internal" envelopes of the stimuli provide sufficient information. These aspects of the data appear to be consistent with Colburn and Esquissaud's (1976) notion that frequency-related differences in sensitivity to ITD stem from frequency-related differences in the neural information that serves as input to the binaural portion of the auditory system.

On the other hand, the overall elevation in threshold ITDs observed at 10 kHz for both SAM and transposed stimuli may reflect true across-frequency differences within central binaural mechanisms that process ITDs, at least in terms of how they affect absolute sensitivity to ITDs. In our view, this outcome should not detract from the useful insights provided by Colburn and Esquissaud concerning the fundamental explanation for differences in sensitivity to ITD at low vs high frequencies.

The data obtained at all three center frequencies indicate that, in general, threshold ITDs increased as the rate of modulation was increased beyond 128 Hz. Furthermore, they increased more rapidly with rate of modulation (and more often were unmeasurable) as the center frequency of the stimuli was increased to 10 kHz. These effects cannot be explained by simply assuming that peripheral bandpass filtering causes reductions in depth of modulation of the stimuli as rate of modulation is increased and that this, in turn, degrades the binaural processing of ITDs. According to that line of argument, increasing the center frequency of the stimuli would lead to *improved* performance at the higher rates of modulation because the attendant increases in the bandwidths of the auditory filters would produce *relatively less reduction* in the depth of modulation of the stimuli. The data are not in accord with such an expectation. Instead, they appear to be consistent with there being some mechanism that serves to limit the ability to ''follow'' or to encode high rates of fluctuation of the envelope of high-frequency, complex waveforms.

IV. QUANTITATIVE ACCOUNTS AND INTERPRETATIONS OF THE DATA

We attempted to account for the data quantitatively by assuming that the listener's threshold ITDs reflect a constant change of the normalized interaural correlation. The mathematical model used to make the predictions was one we employed in previous studies (Bernstein and Trahiotis, 1996b; Bernstein *et al.*, 1999). It included ''envelope compression'' (exponent$=0.23$), square-law rectification, and low-pass filtering at 425 Hz to capture the loss of neural synchrony to the fine structure of the stimuli that occurs as the center frequency is increased (Weiss and Rose, 1988). For this study, the model was supplemented by an initial stage of bandpass filtering via Gammatone filters (see Patterson *et al.*, 1995) which, like the stimuli, were centered at either 4, 6, or 10 kHz.

In order to make the predictions, it was necessary to determine functions relating ITD to normalized interaural correlation. This was done separately for SAM and transposed stimuli at each of the three center frequencies and at each of a large set of rates of modulation that included those actually used in the experiment. Numerical measures were obtained by implementing the peripheral stages of the model with MATLAB and then computing the normalized interaural correlation between the model's ''left'' and ''right'' outputs for a wide range of ITDs. Then, using a least-squares criterion, polynomials were fit to the paired values of normalized correlation and ITD.

In order to arrive at predicted threshold ITDs, we sought the criterion value of normalized interaural correlation that maximized the amount of variance accounted for between predicted and obtained values of threshold ITD for data obtained with both SAM and transposed stimuli. A separate fitting procedure was carried out for the mean data at 4, 6, and 10 kHz in order to determine whether the criterion values of interaural correlation depended on center frequency. Stimulus conditions for which a mean threshold could not be computed (see Figs. 3 and 5) were not included in the computations of the amount of variance accounted for by the model. Nevertheless, predictions for such stimulus conditions were computed in order to determine what the model would predict.

The three panels of Fig. 7 contain the mean threshold ITDs for the SAM (squares) and transposed (circles) stimulus conditions along with the predictions from the model shown as dotted lines. The solid lines will be discussed below. Qualitatively and in general, the model appears to predict successfully the threshold ITDs for both SAM and transposed stimuli having rates of modulation of 32, 64, or 128 Hz. Quantitatively, the amount of variance in the data accounted[3] for by the model for those three frequencies of modulation was only 43% at 4 kHz, 10% at 6 kHz, and 64% at 10 kHz. At higher rates of modulation, the model fails to capture the dramatic increase in thresholds as the rate of modulation was increased to and beyond 256 Hz.

In an attempt to provide a satisfactory account of the loss of sensitivity to ITD at the higher rates of modulation, we further augmented the model by adding a final stage of monaural, 150-Hz low-pass filtering. The cutoff frequency was the same as that used by Kohlrausch *et al.* (2000) and Ewert and Dau (2000). The new predictions are indicated by the solid lines within each panel of Fig. 7 and appear to provide an improved fit to the data, especially for threshold ITDs obtained at center frequencies of 4 and 6 kHz. At those two center frequencies, the augmented model appears to account both for the elevated thresholds obtained at a rate of modulation of 256 Hz and for the fact that the average listener was essentially unable to perform the task at a rate of modulation of 512 Hz. For stimulus conditions for which a mean threshold could be defined, the amount of variance in the data that was accounted for by the model was 86% at 4 kHz, 96% at 6 kHz, and 77% at 10 kHz. It should be noted that a second-order low-pass filter was required to fit our binaural data, while a first-order filter appeared to fit the data of Kohlrausch *et al.* (2000) and Ewert and Dau (2000). The reasons for this difference are not understood at this time.

The changes of normalized interaural correlation ($\Delta\rho$) computed with the model (after bandpass filtering, compression, rectification, and low-pass filtering) required to fit the data were 0.000 23 at 4 kHz, 0.000 51 at 6 kHz, and 0.001 70 at 10 kHz. At face value, these values of $\Delta\rho$ suggest that sensitivity to envelope-based $\Delta\rho$ declines with increasing center frequency. This type of finding is consistent with our

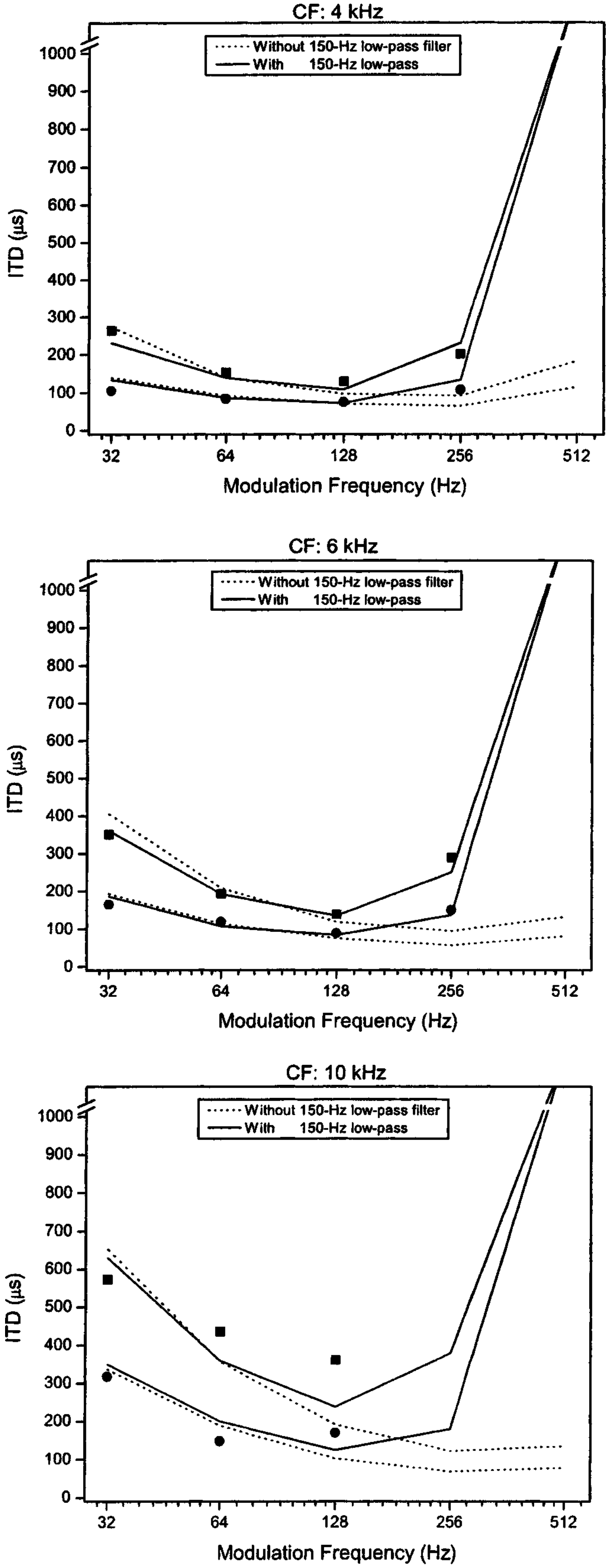


FIG. 7. Threshold ITDs for the SAM (squares) and transposed (circles) stimuli replotted from Figs. 3 and 5. The dotted lines represent predictions based on a constant criterion change in the normalized correlation computed subsequent to compression, rectification, and low-pass filtering at 425 Hz (see the text). The solid lines represent predictions obtained when the peripheral processing was supplemented by an additional 150-Hz low-pass filter.

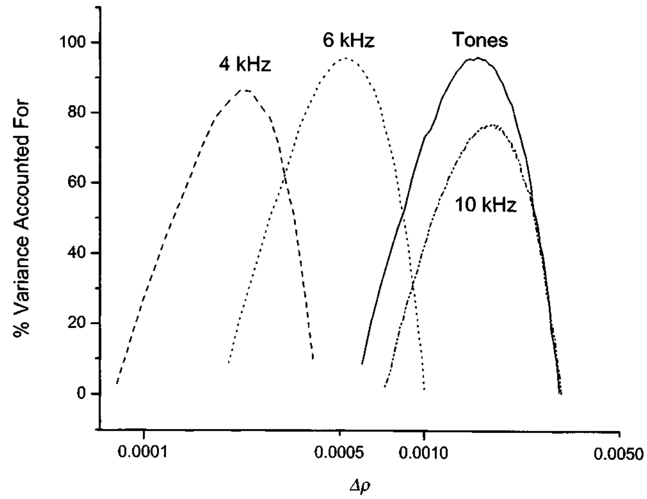


FIG. 8. Variance accounted for by the predictions as a function of the criterion $\Delta\rho$ for the pure-tones stimuli and for the stimuli centered at 4, 6, and 10 kHz, respectively.

previous research (Bernstein and Trahiotis, 1994). In order to evaluate the relative precision of the fits to the data obtained across center frequency in this study, we recomputed the percentages of variance accounted for at each center frequency while varying the criterion value of $\Delta\rho$. Figure 8 shows the results of the computations. The peaked nature of the plots indicates quite clearly that the fits are relatively precise and robust because relatively small changes in the criterion value of $\Delta\rho$ lead to relatively large changes in the amounts of variance accounted for. Furthermore, there is little overlap among the individual plots corresponding to fits obtained at the different center frequencies. Based on these findings it appears that our data and analyses are sufficiently precise to support the conclusion that sensitivity to envelope-based $\Delta\rho$ declines as center frequency is increased from 4 to 10 kHz.

Figure 8 also contains a plot of variance accounted for as a function of criterion $\Delta\rho$ for the tonal stimuli having frequencies of 128, 256, and 512 Hz. The mean threshold obtained at 64 Hz was excluded from the analysis because, as discussed much earlier in this presentation, it was not representative of performance measured across the four listeners. The 150-Hz low-pass filter was not included in the model because its function is to attenuate *modulations of amplitude* which are not present in tonal stimuli. In fact, including such a filter would appear to be folly because it would severely attenuate the internal, rectified representation of the signal and lead to the absurd prediction that sensitivity to ITD declines dramatically as the frequency of the signal increases beyond 150 Hz.

For the low-frequency tones, the criterion value of $\Delta\rho$ that best fit the data was 0.001 54. The plot representing the fits peaks in the region of 96% of variance accounted for, indicating that a correlation-based model that incorporates stages of peripheral auditory processing provides an excellent account of how threshold ITDs vary with frequency for pure tones. Note also that the plot representing the fits with the tonal stimuli overlaps greatly with the plot representing the fits for threshold ITDs obtained at a center frequency of

10 kHz. Therefore, based on the values of $\Delta\rho$ shown in Fig. 8, it appears that listeners are *least* sensitive to changes in interaural correlation for low-frequency pure tones and SAM and transposed stimuli centered at 10 kHz.

This outcome is somewhat counterintuitive because, as mentioned at the very beginning of this paper, threshold ITDs measured with low-frequency pure tones are typically smaller than those measured when the ITDs are conveyed by the envelopes of high-frequency stimuli. In fact, the data in Figs. 3 and 5, indicate that this is so. *A priori*, within a correlation-based approach, one might expect that values of threshold ITD and their $\Delta\rho$ counterparts would vary in a one-to-one fashion. For any particular stimulus, that is certainly the case. Considered across types of stimuli, however, such a relation does not occur. Specifically, the small threshold ITDs found with low-frequency tones correspond, through our model, to larger values of $\Delta\rho$ than do, for example, the larger threshold ITDs obtained at 4 and 6 kHz. This comes about because the empirically measured functions relating $\Delta\rho$ to ITD for the low-frequency pure tones are steeper than those measured for the high-frequency stimuli.

In an attempt to understand what aspect or aspects of the model lead to this outcome, we performed several computer-based analyses while omitting one or more of the peripheral stages of the model. It appears that the factor that is responsible is the differential effect that compression has on tonal stimuli and on the high-frequency complex waveforms. The type of ''envelope compression'' employed simply scaled the amplitudes of the pure tones but imposed a true compressive nonlinearity on the envelopes of the high-frequency SAM and transposed waveforms.

We investigated the effects of removing compression from the model. Doing so drastically reduced the amounts of variance accounted for. This was not completely unexpected because in a prior investigation (Bernstein *et al.*, 1999) we had demonstrated that the inclusion of envelope-based compression was necessary in the sense that it allowed us to account for binaural detection with maskers of divergent temporal features. In that study, we demonstrated that the data could not be accounted for if compression were not included. In addition, the form of compression used in the model is not arbitrary. Rather, it conforms to physiologically-based measures of basilar-membrane motion (e.g., Ruggero *et al.*, 1997) and is also constrained by successful fits to behavioral detection data obtained in independent investigations. For all these reasons, we believe that the form of compression used in the model is appropriate and that the differences in $\Delta\rho$ that account for the data are valid.

At this time, we can offer no satisfactory explanation for why listeners are relatively more sensitive to changes in $\Delta\rho$ conveyed by high-frequency stimuli centered at 4 and 6 kHz than they are to changes in $\Delta\rho$ conveyed by low-frequency pure tones of 128, 256, and 512 Hz. Our only speculation is that binaural detection is known to be constrained by additive ''internal noise'' which appears to decline dramatically for frequencies above 100 Hz (e.g., Shaw and Piercy, 1962). Yost (1988) has demonstrated that such internal noise also limits the magnitude of the MLD at low frequencies even when insert earphones, like the ones used in this study and which tend to attenuate this type of internal noise, are employed.

V. SUMMARY

Following van der Par and Kohlrausch (1997), we employed a procedure termed ''transposition'' in an attempt to provide the high-frequency channels of the auditory system with information like that normally available only at low frequencies. In these experiments, transposition entailed multiplication (modulation) of a high-frequency sinusoid by a rectified, low-pass filtered, low-frequency tone. Our findings indicate that threshold ITDs obtained with the transposed stimuli were generally smaller than those obtained with SAM tones and, at modulation frequencies of 128 and 64 Hz, were equal to or smaller than threshold ITDs obtained with their low-frequency pure-tone counterparts. Our quantitative analyses revealed that the data could be well accounted for via a model based on normalized interaural correlations computed subsequent to known stages of peripheral auditory processing augmented by low-pass filtering of the envelopes within the high-frequency channels of each ear. The data and analyses appear to be consistent with the general ideas advanced by Colburn and Esquissaud at a meeting of the Acoustical Society of America in 1976. They conjectured that the greater potency of ITDs typically observed for low frequencies as compared to high frequencies results from differences in the specific aspects of the waveform that are coded peripherally rather than from differences in the more central binaural mechanisms that process information from the different frequency regions. It should be understood that, in principle, any of a variety of high-frequency stimuli other than transposed ones, may, because of the temporal characteristics of their envelopes, foster enhanced sensitivity to ITDs. This would not detract from the general validity of the suggestions made by Colburn and Esquissaud so long as a model that assumes that a common *binaural* mechanism operates across frequency (such as the model employed here) is able to account for the data.

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[1]We were surprised to find that stimulus levels produced according to the calibration supplied with the Etymotic ER-2 earphones sounded less loud than stimuli presented at nominally the same level via TDH-39 earphones, according to their calibration. Dr. Mead Killion, of Etymotic Research, validated our listening experience and agreed with us that the two respective methods of calibration would be expected to produce levels of stimulation differing by about 10 dB. We chose to ''calibrate'' the outputs of the Etymotic earphones to the nominal levels produced by the TDH-39s so that listeners in this study would receive levels of stimulation directly comparable to those utilized by us and others in prior psychophysical experiments employing TDH-39s. We verified that the levels from the Etymotic earphones were appropriate by presenting a high-frequency, stimulus to one ear via an Etymotic ER-2 earphone and simultaneously to the other ear via

a TDH-39 earphone. We then adjusted the relative levels between the two ears to produce a "centered" intracranial image, as is produced by diotic stimuli in normal-hearing listeners. In order to produce a centered image, it was necessary to impose a 10-dB larger voltage on the Etymotic ER-2 than would be expected on the basis of its calibration. Incidentally, the same type of ear-to-ear comparison allows one to compare and to cross calibrate any earphone to any other one, local variations in the frequency response of the earphones notwithstanding.

[2]In order to make this comparison, the values of ITD reported by Henning (1974) must be doubled. Henning introduced an ITD once per trial to the left or right ear. This provided twice as much information as compared to introducing the ITD to the same ear, once per trial, as in the current study and the study by Bernstein and Trahiotis (1994). Nueztel and Hafter (1981) employed a procedure similar to Henning's but the thresholds they report are twice the value of the ITD presented in each interval.

[3]The formula used to compute the percentage of the variance for which our predicted values of threshold accounted was $100\times(1-[\Sigma(O_i-P_i)^2]/[\Sigma(O_i-\overline{O})^2])$, where O_i and P_i represent individual observed and predicted values of threshold, respectively, and $\overline{O}$ represents the mean of the observed values of threshold.

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