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Measures of extents of laterality for high-frequency “transposed” stimuli under conditions of binaural interference

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Abstract

The purpose of this study was to determine whether across-frequency binaural interference would occur if ITD-based extents of laterality were measured using high-frequency transposed stimuli as targets. The results of an earlier study [L. R. Bernstein and C. Trahiotis, *J. Acoust. Soc. Am.* **116**, 3062–3069 (2004)], which focused on threshold-ITDs, rather than extents of laterality, suggested that high-frequency transposed stimuli might be “immune” to binaural interference effects resulting from the addition of a spectrally-remote, low-frequency interferer. In contrast to the earlier findings, the data from this study indicate that high-frequency transposed targets are susceptible to binaural interference. Nevertheless, high-frequency transposed targets, even when presented along with an interferer, yielded greater extents of ITD-based laterality than did high-frequency Gaussian noise targets presented in isolation. That is, the “enhanced potency” of ITDs conveyed by transposed stimuli persisted even in the presence of a low-frequency interferer. Predictions made using an extension of the model of Heller and Trahiotis [L. M. Heller and C. Trahiotis, *J. Acoust. Soc. Am.* **99**, 3632–3637 (1996)] accounted well for across-frequency binaural interference obtained with conventional Gaussian noise targets but, in all but one case, over-predicted the amounts of interference found with the transposed targets.

Introduction

Several experiments concerning binaural hearing have demonstrated that sensitivity to an ongoing interaural temporal disparity (ITD) conveyed by a high-frequency “target” can be degraded by presenting a simultaneously gated, diotic, low-frequency “interferer.” This general outcome is termed binaural interference in order to differentiate it from other deleterious effects, such as masking. Binaural interference has been demonstrated both in experiments concerning the detection of ITDs and in experiments concerning extents of the laterality produced by ITDs. (e.g., McFadden and Pasanen, 1976; Davis, 1985; Zurek, 1985; Dye, 1990; Trahiotis and Bernstein, 1990; Bernstein, 1991; Buell and Hafter, 1991; Woods and Colburn, 1992; Buell and Trahiotis, 1993; Stellmack and Dye, 1993; Bernstein and Trahiotis, 1992; 1995; Heller and Trahiotis, 1995b, 1996; Bernstein and Trahiotis, 2004)

One explanation offered to account for binaural interference is that it stems from a “non-optimal” combination of ITD-information conveyed by the target and the interferer, respectively (e.g., Buell and Hafter, 1991; Heller and Trahiotis, 1995b, 1996; Bernstein and Trahiotis, 2004). Within that view, the ITD-value of zero carried by the low-frequency diotic interferer is combined with the ITD carried by the high-frequency target. As a consequence, the “internal” effective magnitude of the ITD conveyed by the target is diminished as compared to what it would be in the absence of the interferer. For that reason, ITDs imposed on the high-frequency target must be increased: 1) in order to reach threshold and 2) in order to produce an extent of laterality comparable to that obtained in the absence of the interferer.

Bernstein and Trahiotis (2004) have recently shown that across-frequency binaural interference effects as measured via ITD-thresholds were, for all practical purposes, absent when certain “transposed” stimuli served as high-frequency targets. Transposed stimuli are specially constructed in order to provide high-frequency auditory channels with envelope-based temporal information that mimics waveform-based temporal information normally available only in low-frequency channels (see van de Par and Kohlrausch, 1997; Bernstein and Trahiotis, 2002; 2003; 2004).

The purpose of this study was to determine to what degree binaural interference would occur if extents of laterality, rather than resolution of ITD, were measured using high-frequency transposed stimuli as targets. It has long been recognized, using conventional stimuli, that one cannot predict extents of laterality solely from measurements of threshold-ITDs made with the same stimuli (e.g., Stern and Colburn, 1978; Bernstein and Trahiotis, 1985; Trahiotis et al., 2001). Therefore, it seemed important to determine whether interference effects would be revealed when extents of laterality, a type of “supra-threshold” measure of potency of ITD, were the focus.

I Experiment

A. Procedure

Two sets of four high-frequency stimuli served as targets and each set of four will be described and justified in turn. The first set of four consisted of: 1) a 200-Hz-wide band of Gaussian noise centered at 4 kHz; 2) a 128-Hz tone transposed to 4 kHz; 3) a 50-Hz-wide band of Gaussian noise centered at 125 Hz transposed to 4 kHz; 4) a 100-Hz-wide band of Gaussian noise centered at 125 Hz transposed to 4 kHz.¹

Examples of each of the four types of high-frequency target-stimuli composing this first set are depicted in Figure 1. The left-hand panels show randomly chosen 50-ms epochs of each type of target; the right-hand panels show their (long-term) power spectra calculated over tens of seconds. Beginning with the left hand panels, note that six or seven envelope-maxima occur for each type of target during the 50-ms epochs. That is so because the number of envelope-maxima per second for each type of target is about 125. This corresponds to the rate of the low-frequency stimuli that were transposed to 4 kHz and is the expected number of envelope-maxima per second for a 200-Hz-wide band of Gaussian noise (see Rice, 1954).

The primary reason for choosing a rate of envelope fluctuation near 125 Hz was that transposed stimuli having a similar rate of envelope-fluctuation have been shown to produce the greatest enhancements (relative to their conventional counterparts) of ITD-processing at high frequencies (e.g., van de Par and Kohlrausch, 1997; Bernstein and Trahiotis, 2002; 2003). Therefore, using such a rate would help to maximize observed differences in extents of laterality between the transposed and conventional stimuli. Furthermore, using such a rate causes more than 99% of the energy of the transposed stimuli to fall between the sidebands centered at 3750 Hz and 4250 Hz (see right-hand panels of Fig.1). As a result, only minimal amounts of energy associated with each transposed target would fall outside the approximately 500-Hz wide auditory filter centered at 4 kHz (see Moore, 1997). It was judged that having all

¹The frequency of the tone that was transposed to 4 kHz was chosen to be 128 Hz in order to match the frequency that was employed in our earlier studies (Bernstein and Trahiotis, 2002; 2004). The center frequency of the low-frequency bands of noise that were transposed to 4 kHz was chosen to be 125 Hz in order to match the center frequency employed in our earlier study of extents of laterality using transposed noises. The same considerations dictated the choice of 256 Hz and 250 Hz for the transposed tone and noises, respectively, which composed the second set of targets described later in the text. These very small disparities within each set of targets between the frequencies of the tones and the center frequencies of the noises that were transposed to 4 kHz are, for all practical purposes, inconsequential.

stimuli satisfy this latter constraint would enhance the validity of comparisons among the data obtained with the various targets and, perhaps, simplify interpretations of the results.

The second set of four targets consisted of: 1) a 400-Hz-wide band of Gaussian noise centered at 4 kHz; 2) a 256-Hz tone transposed to 4 kHz; 3) a 50-Hz-wide band of Gaussian noise centered at 250 Hz transposed to 4 kHz; 4) a 100-Hz-wide band of Gaussian noise centered at 250 Hz transposed to 4 kHz. Note that the rates of envelope fluctuation of these four targets are twice those of their counterparts in the first set of targets. Despite this difference, 90% of the energy associated with each of the transposed targets in the second set also fell within the sidebands centered at 3750 Hz and 4250 Hz.

The major reason for employing the second set of targets was that increasing the rate of fluctuation of transposed noises from 125 Hz to 250 Hz has been shown to result in *somewhat smaller* extents of laterality (Bernstein and Trahiotis, 2003). In contrast, for conventional bands of Gaussian noise, increasing the rate of envelope fluctuation from about 125 Hz to about 250 Hz by increasing bandwidth from 200 Hz to 400 Hz has been shown to result in *somewhat greater* extents of laterality across values of ITD (e.g., Bernstein and Trahiotis, 2003). Mindful of these results, it seemed prudent to assess the degree to which amounts of interference measured with the second set of stimuli would be commensurate with those measured with the first set of stimuli. Of special interest was whether transposed noises in the second set, which have been shown to yield relatively less enhancement of ITD processing in terms of extent of laterality, would be relatively more susceptible to across-frequency binaural interference. Posed differently, would the “less-robust” processing of ITD supported by the transposed noises in the second set of targets result in more binaural interference?

The transposed stimuli were generated in the manner described by Bernstein and Trahiotis (2002; 2003; 2004). Briefly, the time-domain representation of a narrow band of low-frequency Gaussian noise or a low-frequency tone was (linearly) half-wave rectified. This was accomplished by setting all negative values to zero. Then, the rectified waveforms were transformed to the frequency-domain and all spectral components above 2 kHz were removed by setting their magnitudes to zero (see pp 1027–1028 of Bernstein and Trahiotis (2002) for a justification of the choice of this type of rectification and filtering). Following this, each rectified and filtered waveform was transformed back to the time-domain and multiplied by a 4-kHz sinusoidal “carrier.” This procedure resulted in transposed stimuli each having an envelope with a time signature that mimicked that of the rectified and filtered low-frequency narrow band of noise (or low-frequency tone) used to generate it.

The stimulus that served as the interferer was a diotic 400-Hz-wide band of Gaussian noise centered at 500 Hz. That stimulus has been shown to produce substantial amounts of binaural interference, as indexed by threshold-ITDs, for conventional stimuli centered at 4 kHz (e.g., Bernstein and Trahiotis, 1995; 2004).

All stimuli were generated digitally as seconds-long buffers using 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. Targets and interferers were each presented at a level matching 72 dB SPL as produced by TDH-39 earphones in a 6-cc coupler.² For all stimuli that served as targets, ongoing ITDs (0, 200, 400, 600 μ s, left ear leading) 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.

Four normal-hearing young adults (one male and three female) who had each participated in previous binaural experiments served as listeners. Extents of laterality were measured via an acoustic pointing task in which the listeners varied the interaural intensive difference (IID) of a 200-Hz-wide band of noise centered at 500 Hz (the pointer) so that it matched the

intracranial position of a second, experimenter-controlled, stimulus (the target). This procedure has been used previously in several studies (e.g., Trahiotis and Stern, 1989; Buell et al., 1991; Heller and Trahiotis, 1996) and is described fully in Bernstein and Trahiotis (1985). The overall level of the pointer, when presented diotically (IID=0 dB), was 65 dB SPL. Listeners adjusted the intracranial position of the pointer by rotating a knob. Rotation of the knob produced symmetric changes of the IID (in dB) of the pointer (i.e., increases in level at one ear and decreases in level at the other ear). The IID adjusted by the listener served as a metric of the intracranial position of the target. A value of IID was chosen randomly from the range ± 4 dB (in 0.5-dB steps) and was inserted in the pointer prior to each match. This served to randomize the initial position of the pointer with respect to the absolute position of the knob. Each sequence of stimuli consisted of three presentations of the target (each separated by 200 ms), a pause of 300 ms, three presentations of the pointer (each separated by 200 ms) and a pause of 600 ms. The duration of target and pointer stimuli was 100-ms including 20-ms $\cos^2$ rise/decay and each was extracted from the appropriate longer buffer.

Targets and pointers were repeated until the listeners indicated that they had matched the intracranial positions of the target and pointer. Prior to completing a match, listeners had the option of halting, and then restarting, the sequence in order to “check” their adjustments after a period of silence.

Testing began by measuring extents of laterality in the absence of the interferer. All of the aforementioned targets were visited in pseudo-random order. Having chosen a particular stimulus condition as the target, a random process was used to select a value of ITD from the set to be tested until the listeners had completed three independent matches for each value of ITD. The mean IID inserted by the listener to match the diotic targets (ITD = 0) served as a “correction factor.” That is, it was subtracted from the IIDs resulting from all the matches in the run. Any series of matches that yielded a correction factor with a magnitude greater than 5 dB was discarded and re-run until a “valid” series was obtained with a correction factor less than that value. After matches were made in all of the “without-interferer” conditions, the same stimulus conditions were re-visited in reverse order. Finally, the entire process was repeated for targets presented in the presence of the simultaneously-gated low-frequency interferer. The data reported in the figures represent the mean “corrected” value of IID of the pointer across the six valid matches made by each listener for a particular combination of target and ITD.

B. Results and discussion

In all of the plots of the data that follow (Figs. 2–4), filled squares represent data obtained in the absence of the interferer and open triangles represent data obtained in the presence of the interferer. Only the data averaged across the four listeners will be presented because between-listener differences were small, as indicated by the error bars which represent $\pm$ one standard error of the mean. Table I contains information regarding the within-listener precision with which the matches were made. The average standard deviation was computed for each value of ITD tested. This was done separately for the no-interference and interference conditions. Each entry in the table represents the mean of the 32 (eight targets X four listeners) measures

²Stimulus 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, notwithstanding local variations in the frequency response of the earphones.

of standard deviation computed across the six matches made by each listener for each experimental condition. Note that the average, within-listener standard deviation increases with ITD, being only slightly larger than 1 dB when the targets were presented diotically and increasing to about 2.5 ± 0.25 dB when the ITD was 600 μ s. This indicates that the precision of binaural processing is greater for stimuli perceived near midline than for stimuli that are perceived to be lateralized well toward the ear. This is in accord with the findings of previous studies (e.g., Mills, 1958; Hafer and DeMaio, 1975; Domnitz and Colburn, 1977). The standard errors of the means indicated in the figures taken together with the standard deviations appearing in Table I, indicate that both the within- and between-listener variance was small in comparison to, and need not constrain interpretations of, the magnitude of the differences found between conditions.

The solid lines within the figures are the best linear-regression fits to the data with the intercept forced to be zero. An intercept of zero is consistent with our use of “correction factors” for matches made with diotic targets. Using the correction factors forces the empirical match to an ITD of 0 μ s to be 0 dB of IID of the pointer. The dashed lines within the figures represent quantitative predictions of extents of laterality in the presence of the interferer. Those predictions are discussed in section IC.

A summary of the statistical analyses that will be used to help interpret the data is presented in Table II. The first column of the table indicates the type of target. The second column of the table contains the slopes of the best-fitting lines to the data for each target when it was presented in the absence of the interferer. The third column indicates the amount of variance accounted for by the fitted line forced through the origin.³ The fourth and fifth columns contain the same types of information for the conditions in which the interferer was presented along with the target. The sixth column contains the ratio of the “without-interferer” slope to the “with-interferer” slope for each target. Because, as will be discussed, the data are well-fit by straight lines passing through the origin, the ratio of the value of the pointer-IID obtained in the without-interferer condition to the value obtained in the with-interferer condition can be taken to be constant for all values of ITD of the target. Therefore, the ratio of the slopes provides a consistent measure of binaural interference independent of the perceived intracranial loci of the targets. Bernstein and Trahiotis (1995) used similar types of ratios to quantify binaural interference in an experiment measuring threshold-ITD, threshold-IID, and thresholds for the detection of a signal in noise.

The seventh and eighth columns show the F-ratios and their associated probabilities derived from a statistical analysis (Edwards, 1964) that yields the significance of the differences of the regression slopes (calculated using the mean data) obtained for the targets presented in isolation versus when they were presented along with the interferer. This type of statistical analysis was deemed appropriate because it is the amount of the disparity between the two slopes that directly (i.e., independently of the magnitude of ITD) reflects the amount of binaural interference that occurred.

Asterisks indicate significance using an alpha-level of $p < 0.05$. The percentages of variance accounted for by the linear fits (columns 3 and 5), being, in the great majority of cases between 97 and 99%, indicate that the data are well fit by straight lines having an intercept of zero. Given the quality of the linear fits, the ratio of the slopes obtained for “without interference” and for “with interference” conditions can be taken as valid descriptors of the amounts of interference produced for each target.

³The formula used to compute the percentage of the variance for which our predicted values of pointer-IID (in dB) accounted was $100 \times (1 - [\Sigma(O_i - P_i)^2] / [\Sigma(O_i - \bar{O})^2])$ where O_i represents the average observed values and P_i represents the predicted values. $\bar{O}$ represents the grand mean of the observed values of IID.

Panels a and b of Figure 2 display the results obtained when 200-Hz-wide and 400-Hz-wide bands of Gaussian noise, respectively, served as targets. Note that only modest extents of laterality were obtained when the high-frequency Gaussian-noise targets were presented in isolation (filled squares), the largest values of the IID of the pointer being only 6–7.5 dB when the ITD was as large as 600 μ s. Such values of IID are substantially less than the 10–12 dB or so that have been commonly found to indicate intracranial images lateralized near the leading ear (see Watson and Mittler, 1965; Yost, 1981; Trahiotis and Bernstein, 1986). Comparison of the data in panel b to those displayed in panel a reveals that slightly greater extents of laterality were obtained when the bandwidth of the target was increased from 200 to 400 Hz.

Most important for our purposes, for both of the Gaussian-noise targets, extents of laterality were diminished with the addition of the simultaneously-gated low-frequency noise (open triangles), thereby indicating binaural interference. The degree of across-frequency binaural interference is quantified by the ratios of the without-interferer to with-interferer slopes that can be found in the fifth column of Table II. For the data obtained with the two Gaussian noise targets, the ratios of the slopes were 5.65 (200-Hz-wide noise) and 2.61 (400-Hz-wide noise). As indicated by the right-most column of the table, the underlying pairs of slopes for these two targets were significantly different. Note that the slope-ratios for these Gaussian-noise targets are the largest in the table. This indicates that the largest interference effects occurred with these two conventional Gaussian-noise targets. In fact, the relatively small values of the IID of the pointer required to make matches in the presence of the interferer for those two targets indicates intracranial positions of the targets quite close to or at midline. The only seemingly poor linear fit to the data occurred when the 200-Hz-wide Gaussian-noise target was presented along with the interferer. As indicated in Table II, the linear fit to these data accounted for only 60% of the variance. This outcome should be interpreted with caution for two reasons. First, as shown in Fig. 2a, in the presence of the interferer, there was virtually no ITD-based lateralization and, therefore, virtually no variance above and beyond the noise of measurement for which to account. Secondly, the best fitting line deviates, at most, by about 0.5 dB from the data. Overall, the extents of laterality and the amounts of interference obtained with the Gaussian-noise targets are entirely consistent with and essentially replicate patterns of data reported in our earlier studies (Bernstein and Trahiotis, 1995; 2003; Heller and Trahiotis, 1996).

We now turn to the data of most interest, those obtained with high-frequency, transposed stimuli. Panel a of Figure 3 displays data obtained when the target was a 128-Hz pure tone transposed to 4 kHz. Two effects are apparent. First, ITDs conveyed by the transposed target presented in isolation resulted in larger extents of laterality as compared to the Gaussian-noise targets when they were presented in isolation. For example, an IID of the pointer of 10 dB was required to match the intracranial position of the target when the ITD was 600 μ s. This indicates an intracranial image near the leading ear and is typical of the extent of laterality produced by a 600- μ s ITD conveyed by a *low-frequency* stimulus. Second, the addition of the interferer had no effect. This is confirmed quantitatively in Table II in that the ratio of the without-interferer to with-interferer slopes is 1.01 for this target. Furthermore, as also indicated in the table, the 128-Hz transposed target is the *only* one for which the difference between the two underlying slopes is not significant.

This set of observations, taken together, supports the conclusion that adding the diotic low-frequency interferer had *no effect* on ITD-based lateralization for this target. A similar apparent “immunity” to across-frequency binaural interference was found with the same stimulus when threshold-ITD, rather than extent of laterality, was the dependent variable (Bernstein and Trahiotis, 2004).

Panels b and c of Fig. 3 display data obtained when the target was either a 50-Hz-wide or a 100-Hz-wide band of noise centered at 125-Hz and transposed to 4 kHz. Note that these two transposed-noise targets consistently produced larger extents of laterality than did the transposed tone (panel a) in the absence of the interferer (filled squares). For example, for the transposed noises, the listeners required about 11 dB of IID in the pointer, indicating an image just at the leading ear when the ITD was only 400 μ s. Furthermore, an IID of about 15 dB was required to match an image when the ITD was 600 μ s. These extents of laterality are very similar to those reported with the same stimuli by Bernstein and Trahiotis (2003). At this time, we cannot account for the finding that the transposed noises produced slightly greater extents of laterality than did the transposed tone. Perhaps this outcome is related to an earlier finding with conventional stimuli, namely that high-frequency Gaussian noises produce greater extents of ITD-based laterality than do high-frequency SAM tones having the same “bandwidth” (Trahiotis and Bernstein, 1986).

Unlike what was found with the transposed tone (panel a), the addition of the low-frequency, diotic noise to the transposed *noises* resulted in interference in that extents of laterality were reduced. As indicated in Table II, the ratios of the lateralization slopes for the two bandwidths were 1.87 and 1.71, respectively, indicating substantial (and statistically significant) binaural interference.

Interestingly, as can be seen by visual inspection of Fig. 3 and by referring to the lateralization slopes in Table II, the extents of laterality measured in the presence of the interferer when the targets were transposed noises were very much like those measured with the 128-Hz transposed-tonal target. In all four cases, the slopes are near 0.015. Thus, the increments in lateralization measured when the ITDs were conveyed by the transposed noises, rather than by a transposed tone, were essentially “neutralized” in the presence of the interferer. That is, in the presence of the interferer, the extents of laterality measured with the transposed tone and the two transposed noises are virtually identical. Note that, even under interference conditions, these transposed stimuli yielded greater (i.e., enhanced) extents of laterality than did conventional high-frequency Gaussian-noise targets *presented in isolation* (compare Fig. 3b with Fig. 2a and b).

The data obtained when the low-frequency stimuli to be transposed were centered near 250 Hz are displayed in Figure 4. Once again, panel a contains data obtained for targets generated by transposing a pure tone, in this case 256 Hz, to 4kHz. Panels b and c contain data obtained when 50-Hz-wide (panel b) or 100-Hz-wide (panel c) Gaussian noise centered at 250 Hz and transposed to 4 kHz served as targets.

The comparisons to be made among the data displayed in the panels of Fig. 4 directly parallel those made among the data presented in Fig. 3. The reader is reminded that the primary reason for employing this second set of transposed stimuli was that low-frequency noises centered on 250 Hz and transposed to 4 kHz have been shown to yield smaller extents of laterality than low-frequency noises centered on 125 Hz (Bernstein and Trahiotis, 2003). The question of interest here was whether such “less-robust” processing of ITD would result in more binaural interference.

For ease of exposition, we begin with the data in panels b and c of Fig. 4. The data show that these transposed targets, when presented in isolation, result in extents of laterality that are substantially *greater* than those obtained with conventional Gaussian-noise targets (compare to Fig. 2) but only slightly *smaller* than extents of laterality measured with their counterparts derived from bands of noises centered on 125 (compare to panels b and c of Fig. 3). These differences are consistent with those reported by Bernstein and Trahiotis (2003). The *amounts of interference*, as quantified by the ratio of the slopes obtained with these targets (1.95 and

1.93, respectively), were slightly greater than those obtained with transposed noise targets derived from noises centered at 125 Hz (1.87 and 1.71, respectively).

Finally, we turn to the data obtained with a 256-Hz pure tone transposed to 4 kHz (Figure 4, panel a). Note that the extents of laterality measured in the absence of the interferer are virtually the same as those obtained with the 128-Hz pure tone transposed to 4 kHz when it was also presented alone (see Panel a of Fig. 3). As seen by considering their respective lateralization slopes of 0.0165 and 0.0182, those two stimuli, when presented in isolation, were lateralized essentially identically. Nevertheless, for the 256-Hz pure tone transposed target, the addition of the low-frequency diotic noise produced *substantial* interference, as evidenced by the ratio of the with-interferer to without-interferer slope-ratio of 1.98. This clearly indicates that this target, unlike its 128-Hz transposed counterpart (Fig. 3a) was, indeed, “susceptible” to across-frequency binaural interference.

The comparisons among the data discussed above do not appear to yield insights regarding 1) which features of transposed targets affect their ITD-based extents of laterality and 2) which features of the transposed targets render them more or less susceptible to across-frequency binaural interference. For example, as can be seen in Fig. 1, the difference between a transposed tone and a transposed noise is manifest as both a change from a deterministic to a stochastic envelope and a change from a discrete “line-spectrum” to one having sidebands characterized by spectral extent or “breadth.” In future experiments, we plan to investigate whether and to what degree various temporal and/or spectral aspects of high-frequency complex waveforms affect their susceptibility to across-frequency binaural interference.

All of these issues notwithstanding, the main findings of the study are quite clear: high-frequency transposed stimuli not only produce greater ITD-based extents of laterality than do high-frequency Gaussian noises but they are, generally speaking, less susceptible to across-frequency binaural interference.

C. Extending and testing a laterality-based quantitative model of binaural interference

In this section, we describe the application to the data described above of an extension of the quantitative model of across-frequency binaural interference described by Heller and Trahiotis (1996). To date, the model has been found to account quantitatively for binaural interference measured via threshold-ITDs when the targets and interferers were sinusoidally amplitude-modulated tones (Heller and Trahiotis, 1996) and when the targets and interferers were narrow bands of Gaussian noise (Bernstein and Trahiotis, 1994). A fundamental underlying assumption of that model is that binaural interference arises from an obligatory, non-optimal, across-frequency-channel, combination of binaural cues. The combining of information is non-optimal because the low-frequency diotic interferers, which convey no information useful for detecting or lateralizing on the basis of ITDs within high-frequency targets, are not ignored. A second important assumption of the model is that it is *the extent of laterality* produced at threshold-ITD that is the crucial variable and not the magnitude of the threshold-ITD itself. The extent of laterality at threshold (in terms of IID of the pointer) is estimated by multiplying the threshold-ITD (in μs) by the lateralization slope (in IID of the pointer/ μs). That extent of laterality is, in turn, used to compute the salience or “weight” of the ITD-based information carried by the target or interferer when each is presented in isolation (see pp. 3066–3068 of Bernstein and Trahiotis, 2004 for a more formal and much more detailed discussion). Computing the weights via empirical measures obtained with targets and interferers presented in isolation allows the model to *predict* the expected amounts of interference when targets and interferers are presented simultaneously. This approach should be differentiated from others in the general literature that compute “weights” derived in a post-hoc manner that are then used as *descriptors* of the relative potencies of the elements in compound stimuli.

In order to compute the predicted lateralization slope for each target in the presence of the interferer, the Heller and Trahiotis (1996) model had to be extended. This was done by assuming that:

$$eff\ s_{t+i} = \frac{a * eff\ s_t + b * eff\ s_i}{a + b} \quad (1)$$

where a and b represent the weights applied to the ITD-based information conveyed by the target and interferer, respectively. The term $eff\ s_{t+i}$ represents the *effective* lateralization slope of the target in the presence of the interferer, $eff\ s_t$ and $eff\ s_i$ represent the *effective* lateralization slopes for the target and interferer, respectively. The effective lateralization slope for the target, $eff\ s_t$, is simply the lateralization slope measured when the target is presented in isolation. The effective lateralization slope for the interferer, $eff\ s_i$, however, is *not* the lateralization slope measured when the extent of laterality of the interferer is measured in isolation because, in the experimental conditions, the interferer carried an ITD of zero *regardless of the value of the ITD of the target*.

The *effective* slope of either the target or the interferer is obtained by multiplying that particular stimulus' lateralization slope (i.e., the one obtained in isolation) by the ratio relating the ITD actually imposed on that particular stimulus to the ITD of the target. In our case, the ITD actually imposed on the target was, of course the ITD of the target itself and, therefore, that ratio is one. This means, as stated above, that the effective slope of the target, $eff\ s_t$, is the same as its lateralization slope measured in isolation. Formally:

$$eff\ s_t = s_t * 1 \quad (2)$$

where s_t is the lateralization slope of the target measured in isolation.

Now, in the interference conditions for which predictions are to be made, the ITD actually imposed on the interferer was always zero. Therefore, the ratio relating the ITD actually imposed on the interferer to the ITD imposed on the target was always zero and, therefore, the effective lateralization slope of the interferer was zero. Formally:

$$eff\ s_i = s_i * 0 \quad (3)$$

where s_i is the lateralization slope of the interferer measured in isolation.

It should be understood that this form of the model takes into account the fact that the targets had ITDs ranging up to 600 μ s while the interferers always carried an ITD of zero, independent of the ITD imposed on the target. On an intuitive level, the model can be seen as attempting to capture the combination of the positive lateralization slope of the target with the effective "zero" lateralization slope of the diotic interferer.

Because only lateralization slopes, and not threshold-ITDs, were measured in the current study, the weights (a and b) were derived from measures obtained in an earlier study that employed stimuli that were essentially identical to those employed here. In the earlier study, both threshold-ITDs and lateralization slopes were measured (Bernstein and Trahiotis, 2004). Three of the four listeners in the current study also participated in that earlier study. The lateralization slopes obtained in the prior and current study for common stimulus conditions were functionally identical. In order to arrive at a prediction for the lateralization slopes measured with targets in the presence of the interferer, the weights, a and b , were entered into equation 1 along with the effective lateralization slopes estimated as described above.

Inspection of Fig. 2 reveals that the predictions of the model (dashed lines) are fairly accurate (within less than 1 dB or so of the obtained data) when the targets were conventional high-frequency bands of Gaussian noise. The model slightly, but consistently, *under-predicts* effects resulting from the addition of the interferer. That is, the model predicts slightly greater extents of laterality in the presence of the interferer than were obtained.

In contrast, inspection of Fig. 3 reveals that, for the “125-Hz” transposed targets, the model consistently and, in many instances substantially, *over-predicts* the effects of adding the interferer. Especially noteworthy is the failure of the model for the data depicted in panel a, when the target was a 128-Hz tone transposed to 4 kHz. In this condition, no interference was observed and the model predicted as much as 5–7 dB of interference depending on the ITD imposed was 400 or 600 μ s.

The finding that the model accounts fairly well for interference effects obtained with conventional high-frequency targets, but over-predicts the degradation produced by the interferer for high-frequency *transposed* stimuli, is consistent with the results of our earlier study which focused on threshold-ITDs (Bernstein and Trahiotis, 2004). Inspection of Fig. 4 reveals that the model accurately predicts the effects of adding the interferer to the 256-tone transposed to 4 kHz and moderately over-predicts the effects of adding the interferer to the two transposed targets derived from Gaussian bands of noise centered at 250 Hz. Overall, the success and failure of predictions of across-frequency interference effects via the Heller and Trahiotis (1996) model in this study parallel those of Bernstein and Trahiotis (2004).

II. General discussion and summary

As a follow-up to Bernstein and Trahiotis (2004), the purpose of this study was to determine whether across-frequency binaural interference would occur if ITD-based extents of laterality were measured using high-frequency transposed stimuli as targets. In the earlier study, which focused on threshold-ITDs rather than extents of laterality, no binaural interference was observed when the targets were high-frequency transposed stimuli. That outcome suggested that transposed high-frequency stimuli might, somehow, be “immune” to across-frequency interference effects commonly found with conventional high-frequency targets.

The data from the current study indicate that high-frequency transposed targets can, indeed, be susceptible to binaural interference when extents of laterality, rather than threshold-ITDs are measured. That is, it appears that whether one observes binaural interference with high-frequency transposed targets depends upon whether threshold-ITDs or ITD-based extents of laterality are measured. It should be emphasized, however, that even when interference occurs, high-frequency transposed targets yielded greater extents of ITD-based laterality than did Gaussian noise targets presented in isolation. That is, enhancements of ITD-based lateralization obtained with high-frequency transposed stimuli, as compared to their conventional counterparts presented in isolation were found even under conditions of across-frequency binaural interference. Predictions made using an extension of the model of Heller and Trahiotis (1996) accounted quite well for binaural interference obtained with conventional Gaussian noise targets but, in all but one case, over-predicted the amounts of interference found with the transposed targets.

One broad implication of the findings in this study, taken together with those of Bernstein and Trahiotis (2004), is that across-frequency binaural interference effects cannot, in general, be accounted for solely by assessing the relative potency and/or salience of ITDs conveyed by targets and interferers when each is presented in isolation. It appears that the types of “black-box” models that have been used to account for across-frequency binaural interference with conventional stimuli (e.g., Buell and Hafter, 1991; Heller and Trahiotis, 1995b, 1996) will have

to be augmented or superceded by a more sophisticated, and probably more mechanistic, approach. The success of such models will depend upon their ability to capture how the stimuli, as processed, determine the “strength” of across-frequency interactions that appear to occur within the binaural system. Based on previous studies, (e.g., Trahiotis and Bernstein, 1990; Heller and Trahiotis, 1995a) across-frequency binaural interference appears, in the main, to be central, rather than peripheral, in origin.

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Figure 1.

Left-hand panels: Randomly chosen 50-ms epochs of the four types of targets employed in the main experiment. Right-hand panels: The long-term power spectra of each of the four types of targets.

Figure 2.

IID of the pointer (in dB) required to match the intracranial position of the target as a function of the ongoing ITD (left ear leading) imposed on a 200-Hz-wide (panel a) or 400-Hz-wide (panel b) band of Gaussian noise. The data points represent the mean values computed across the four listeners. The error bars represent ± 1 standard error of the mean. Squares represent data obtained when the target was presented in isolation; triangles represent data obtained when the target was presented along with the low-frequency interferer. Solid lines represent the best linear-regression fits to the data with the intercept forced to be zero. Dashed lines represent quantitative predictions of extents of laterality in the presence of the interferer. Predictions

were derived from an extension of the Heller and Trahiotis (1996) model described in section IIC of the text.

Figure 3.
Similar to Fig. 2 but for the “125-Hz” transposed stimuli.

Figure 4.
Same as Fig. 3 but for the “250-Hz” transposed stimuli.

Table I

The average standard deviation (in dB) obtained for each ITD in the “no-interference” and “interference” conditions. Each entry in the table represents the mean of the 32 (eight targets X four listeners) measures of standard deviation computed across the six matches made by each listener for each experimental condition.

ITD	No-Interference	Interference
0	1.31	1.19
200	1.94	1.54
400	2.66	2.06
600	2.78	2.25

Table II

The second through fifth columns report the slopes (dB/ μ s) and variance accounted for by the best-fitting lines to the data obtained in each experimental condition. The sixth column contains the ratios of the “without-interferer” to “with interferer” slopes. The two right-most columns of the table show the results of the statistical analysis (Edwards, 1964) yielding the significance of the differences of the regression slopes obtained when the targets were presented in isolation versus when they were presented along with the interferer. Asterisks indicate significance using an alpha-level of $p < 0.05$.

Target	Without-Interferer Slope	% Var. Acc.	With-Interferer Slope	% Var. Acc.	Slope Ratio	F	p
Gaussian-CF: 4 kHz; BW: 200 Hz	0.0085	90.1	0.0015	60.5	5.65	19.43	0.0116 *
Gaussian-CF: 4 kHz; BW: 400 Hz	0.0117	98.4	0.0045	99.3	2.61	62.06	0.0014 *
Transposed-128-Hz tone	0.0165	99.0	0.0163	99.3	1.01	0.13	0.7367
Transposed-CF: 125 Hz; BW: 50 Hz	0.0255	99.0	0.0136	99.0	1.87	40.07	0.0032 *
Transposed-CF: 125 Hz; BW: 100 Hz	0.0257	99.0	0.0150	98.2	1.71	18.85	0.0122 *
Transposed-256-Hz tone	0.0182	98.5	0.0092	96.6	1.98	30.15	0.0054 *
Transposed-CF: 250 Hz; BW: 50 Hz	0.0239	97.4	0.0123	97.7	1.95	12.97	0.0227 *
Transposed-CF: 250 Hz; BW: 100 Hz	0.0232	98.3	0.0120	97.8	1.93	17.10	0.0144 *