Binaural interference in lateralization thresholds for interaural time and level differences[a)]

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Listeners discriminated changes in either interaural time differences (ITDs) or interaural level differences (ILDs) in one noise band (the target) in the presence or absence of an uninformative spectrally-remote second noise band (the interferer). The noise bands had center frequencies of 500 and 4000 Hz and bandwidths of 50 and 400 Hz, respectively. When one band was a target, the other served as an interferer. The interferer was presented either diotically or dichotically with ITDs or ILDs that varied randomly across intervals. "Interference" was defined as occurring if the target thresholds were elevated in the presence of an interferer. For ITD discrimination, interference was greater for the 4000-Hz target than for the 500-Hz target, but for ILD discrimination, interference for the 500-Hz target was greater than or equal to that obtained for the 4000-Hz target. Larger interference effects were obtained when the interferer ITD or ILD was randomly varied, revealing that interference can be large not only for high-frequency targets but also for low-frequency targets with high-frequency interferers. The data are consistent with a model in which listeners combine lateral position across frequency with interaural information weighted according to the accuracy with which positions are encoded in each frequency region.
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I. INTRODUCTION

Listeners' sensitivity to interaural time differences (ITDs) presented in a "target" waveform can be either enhanced or reduced by the presence of additional energy in frequency regions remote from that of the target, depending on the configuration of the interaural information across frequencies. For example, the detection of an ITD can be enhanced by increasing the number of spectral components containing consistent ITDs (Buell and Hafter, 1991; Woods and Colburn, 1992; Stellmack and Dye, 1993). However, sensitivity to the ITD of a target frequency region can be reduced if more spectral components are added diotically (McFadden and Pasanen, 1976; Zurek, 1985; Trahiotis and Bernstein, 1990; Dye, 1990; Buell and Trahiotis, 1993; Heller and Trahiotis, 1995). In such a case, the constant binaural information in the frequency region spanned by the non-target waveform, the "interferer," does not provide any cues for the detection of an ITD. Accordingly, the interferer would not affect performance if the listener could attend solely to the output of an auditory filter/filters which passes the binaural information conveyed by target frequencies and rejects interferer frequencies. In apparent contradiction to this concept of a listening band model, the interferer sometimes degrades performance; this effect is referred to as "binaural interference."

McFadden and Pasanen (1976), Zurek (1985), Trahiotis and Bernstein (1990), and Bernstein and Trahiotis (1995) investigated binaural interference in the detection of ITDs in narrow-band noises. In each of these experiments, ITDs were applied to narrow bands of noise. In McFadden and Pasanen's (1976) experiment, the frequency regions occupied by the target and interferer were remote (500 and 4000 Hz). Others employed a broad-band interferer that contained a notch at the narrow-band target's center frequency (Zurek, 1985; Trahiotis and Bernstein, 1990). In all of these studies, when the target and interferer were gated on and off simultaneously, the amount of binaural interference depended upon the relative frequencies of the targets and interferers. For example, McFadden and Pasanen (1976) found that thresholds for a target centered at 4000 Hz were increased by almost a factor of 2 by the addition of a diotic interferer at 500 Hz. In contrast, little or no binaural interference was obtained for a 500-Hz target when the interferer was at 4000 Hz. A common characteristic of these studies is that discrimination of ITDs in high-frequency regions appears to be diminished by diotic stimuli in the low-frequency region. This same pattern of results has also been found in studies using virtual or free-field sound source localization rather than lateralization (Wightman and Kistler, 1992; Croghan and Grantham, 2010).

The question presently under investigation is why the low-frequency region appears to be dominant. One interpretation of this interference effect is that it results from an interaural image formed by a combination of the lateral po-

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sitions of the target and non-target frequency regions (Heller and Trahiotis, 1996; Best *et al.*, 2007). In these models, the lateral positions combine or influence each other based on some other factor, the most likely one being that they share common onsets and offsets (but also possibly other perceptual grouping factors, cf. Best *et al.*, 2007). In order for this mechanism to account for the asymmetry of the interference effect across high and low frequencies, the crucial issues are (1) the basis for the relative weighting of target and interferer interaural information, and (2) the dimension of the underlying decision variable.

For the first issue, the basis of the relative weighting, the integration model of Green and Swets (1974), provides a quantitative basis for the weights, proving that the optimal weight for each independent channel is its expected change in mean divided by its variance. For example, the mean of the decision variable could be based on the locus of neural activity along a delay line that computes interaural disparities, or it could be lateral position. Either way, in the case of typical interference conditions, the optimal weight for the frequency channel containing the diotic interferer would be zero. This is because, when the interferer remains the same across both intervals of a trial, the change in that channel is zero and so it should contribute nothing to the decision variable. However, whenever interference occurs, this empirically demonstrates that the weight on the interferer is not zero; in this case an explanation of the system's behavior must appeal to less optimal strategies. If the change in mean interaural information within a channel (such as a binaural disparity or lateral position) is not known, then one strategy is to assume that the change in all channels is the same. With that assumption, the relative weights across channels are assured to be inversely proportional to the variance of each channel. Specifically, the known variance of the interaural information in each frequency region would be the basis for the combination of interaural information across low and high frequencies. Because ITD sensitivity is generally greater at lower frequencies than at high frequencies, a sensitivity-related weighting scheme would weight low frequencies more heavily than high frequencies: Low-frequency thresholds would not be changed significantly by the addition of the high-frequency interferer, but high-frequency thresholds would increase, because the low-frequency interferer contributes significantly more to the decision variable.

With regard to the dimension of the underlying decision variable, a successful approach utilizing lateral position has been the weighted combination model of Heller and Trahiotis (1996). They successfully predicted interference effects on high-frequency sinusoidally-amplitude-modulated tones by lower-frequency stimuli. They assumed that the underlying decision variable was lateral position, rather than ITD disparities *per se.* The estimated variance of each target and interferer channel was derived not only from the baseline ITD threshold (the sole measure used in earlier models) but also from measures of extent of laterality. This model does not *a priori* assume that ITDs produce different lateral positions in different frequency regions; rather, it allows the laterality data to indicate this, and in the case of ITDs they provide evidence that the extent of laterality produced by high-frequency signals is not as great as that produced by low-frequency signals for a given ITD. In contrast, a model that does not include lateral position effectively assumes that equal ITDs produce equal means in a disparity-based decision variable, so that the variance in all frequency channels can be estimated by using only baseline ITD thresholds (e.g., Buell and Hafter, 1991, for low-frequency tones; Heller and Trahiotis, 1995, for high-frequency sinusoidally-amplitude-modulated tones). Such disparity-based models predict substantially more interference than is observed.

An alternative explanation of asymmetric interference effects as a function of frequency is that an across-frequency interaction takes place prior to binaural interactions. Because the traveling wave of low-frequency sounds affects the region of the basilar membrane that is maximally displaced by high-frequency stimuli more than *vice-versa*, it is possible that the low-frequency interferer disrupts the encoding of the envelope of the high-frequency target, thereby disrupting critical information for high-frequency lateralization (McFadden, 1975; Henning, 1974), but the low-frequency target is not affected by the high-frequency interferer.

Such a peripheral disruption was considered as an explanation for why low-frequency interferers cause interference for high-frequency targets by McFadden and Pasanen (1976). Regarding this explanation, it should be noted that a monaural interaction would not account for the reduction in the amount of interference that was found when a broadband interferer was presented continuously, as compared to when it was gated simultaneously with the target (Trahiotis and Bernstein, 1990). However, the introduction of a continuous interferer did not completely eliminate interference, leaving a small interference effect that was greatest for targets at the highest center frequency employed (4000 Hz). It is also not clear what types of additional cues might be gained by the presence of a continuous interferer. Therefore, it may be useful to gather further evidence pertaining to the role of monaural interactions in interference, especially if it can be obtained by utilizing simultaneously-gated targets and interferers.

A third explanation for the predominant influence of the lower frequencies in ITD-discrimination tasks is a dominance of the low-frequency region of a more general, possibly central, origin. For example, Bilsen and Raatgever (1973) noted that the information in the frequency region between 600 and 700 Hz largely determines the perceived pitch of dichotically delayed noise as well as the lateralization of wide-band clicks. A hypothesis of a more central origin for low-frequency dominance would generate similar predictions to those of the peripheral disruption mechanism, and yet it may be more amenable to incorporating the effects of temporal organization that are not explained by peripheral interactions, such as the effect of a continuous interferer. This type of explanation does not directly explain why low frequencies dominate in location, nor does it provide a quantifiable prediction under a variety of stimulus conditions. Unfortunately, specific models of such central origin schemes have yet to be provided, preventing a rigorous test of this class of hypotheses.

The current experiment probes these alternative hypotheses concerning the asymmetric interference effect found across low-frequency and high-frequency regions by measuring the effects of two different interaural cues (ITD and ILD) that manipulate the same variable, lateral position, differentially in high- and low-frequency regions. Initially, baseline measures were obtained for the discrimination of the ITD of a target when it was presented alone and when it was presented with a simultaneously-gated diotic interferer. In parallel, the same measures were obtained for the discrimination of the ILD of the target. These two conditions should produce different degrees of frequency asymmetry because the threshold of discrimination for ILDs as a function of frequency is different from that of ITDs. In the absence of an interferer, ILD discrimination thresholds are marginally smaller at 4000-Hz than at 500-Hz for tones (Yost and Dye, 1988) and narrow-band noises (Gabriel *et al.*, 1992). For that reason, when an interferer is added, the operation of a weighted combination that reflects sensitivity to ILDs across frequency would be expected to result in less asymmetry, and less dramatic interference, than that which has been found with ITDs (Heller and Richards, 1991; Heller 1992a, 1992b). On the other hand, if the low-frequency dominance found for ITDs is also found for ILDs, explanations which focus on the frequency region of the interferer *per se*, such as a tendency to weight information in low-frequency regions most heavily, would gain support (e.g., Bernstein and Trahiotis 1995). Although Bernstein and Trahiotis (1995) found that a low-frequency narrowband diotic noise interfered with high-frequency ILD discrimination, they did not test low-frequency targets so as to disentangle this question, whereas Dye (1997) found inconsistent results of ILD interferers.

In order to fully explore the range over which interference occurs, in additional conditions, the interaural cue of the interferer was varied randomly across the two intervals of a two-interval forced-choice experiment. There were both within-cue and across-cue conditions for this randomization. In the within-cue conditions, the ITD or ILD of the interferer was randomized while the ITD or ILD of the target, respectively, was discriminated. This manipulation was expected to increase the potency of the interferer relative to a diotic condition because the interferer would sometimes move in opposition to the target across the two intervals of a trial, effectively reducing the change in the putative decision variable. A larger interference effect could potentially reveal more about the underlying across-frequency weighting scheme. Specifically, if the lateral positions of high-frequency interferers change across intervals in opposition to the low-frequency targets, this could give them sufficient power to disrupt the lateralization of low-frequency targets. This manipulation can better test whether the lateral positions of targets and interferers are always being combined even when the targets are not measurably affected (as has been the case with many low-frequency targets) by revealing evidence of a combination when a high-frequency interferer is more potent. In the across-cue conditions, either ITD or ILD of the interferer was randomized while either the ILD or ITD of the target, respectively, was discriminated. This set of manipulations should permit a comparison between the amount of interference seen as a function of the interaural cue being used. If both ITDs and ILDs can produce effective interference in the discrimination of ILDs and ITDs, we can then ask whether the pattern of results varies as a function of frequency, and whether the effect of frequency mirrors the effectiveness of each interaural cue. In other words, if high-frequency ILDs and low-frequency ITDs are the most potent interferers, that result would be most concisely explained by an underlying decision variable that is a weighted combination of lateral position, as opposed to an account based on either a decision variable operating on isolated interaural disparities, or peripheral disruption, or low-frequency dominance.

II. METHODS

A. Task

In each interval of a two-interval forced-choice paradigm, an interaural disparity (either an ITD or an ILD) was applied to a target band of noise. The interaural disparity favored the left ear on either the first or second interval with equal *a priori* probability, and favored the right ear in the remaining interval. When the ITD of a target was manipulated, the ILD was always zero, and when the ILD was manipulated, the ITD was always zero. The task, as explained verbally to the observers, was to indicate the direction of the change in target position across intervals, left to right versus right to left, by pressing one of two response buttons. In each condition, observers were informed of the frequency region of their target sound (either "high" or "low"). They were advised that it might be helpful to attend to the target and ignore the interferer, but that they should attend to feedback and use whatever strategy led to the highest percent correct possible in each condition.

B. Experimental conditions

Four different measurements of ITD thresholds and ILD thresholds were taken in each frequency region. In the target-alone condition, threshold interaural time delays (ITD thresholds) and threshold interaural level differences (ILD thresholds) were obtained for the target presented alone. In the diotic-interferer condition, the threshold ITD (or ILD) for the target was obtained in the presence of a diotic interferer. In the random-interferer/within-cue condition, the threshold ITD (or ILD) was always obtained in the presence of an interferer whose ITD (or ILD) was randomly varied across the two intervals of a trial. In the random-interferer/across-cue condition, the ITD threshold was obtained when the ILD of the interferer was randomly varied across intervals, and the ILD threshold was obtained when the ITD of the interferer was randomized. In all conditions, the observers' task was to indicate the direction of change in the ITD or ILD of the target across the two intervals of a trial. In none of the conditions was the ITD or ILD of the interferer informative with regard to the listener's task.

C. Stimuli

The target and interferer were bands of Gaussian noise either centered at 500 or 4000 Hz, with bandwidths that were 50 or 400 Hz, respectively. When the target band was centered at 500 Hz, the interferer was centered at 4000 Hz, and *vice-versa.* Stimulus duration was 200 ms including 25-ms cosine-squared onset and offset ramps. The overall level of each band of noise was 65 dB SPL. On each presentation, the overall level of the stimulus was randomly incremented or decremented by an amount chosen from a 10-dB range using increments of 1 dB. Level randomization was used to reduce the effectiveness of monaural cues in the ILD conditions, but it was also applied in the ITD conditions. The ITD or ILD of the target was fixed within a block of 50 trials. The range of target ITD or ILD values used for each individual was selected to generate a range of performance spanning from 65% to 85% correct. When the ITD of the random interferer was varied, the interferer ITD was chosen over a range of ± 600 μs (in ten increments of 120 μs). This ITD range was chosen because it approximately spans the range of ITDs that could be produced by a real source. When the ILD of the interferer was random, the interferer ILD was randomly chosen on each interval over a uniform range of ± 10 dB (in ten increments of 2 dB). The same range of ± 10 dB ILD randomization was applied to the 500-Hz interferer even though the changes exceed the ILD that would occur using a real source. This was justified because ILD moves the lateral position of low-frequency stimuli to approximately the same extent that it moves high-frequency stimuli (e.g., Trahiotis and Bernstein, 1986).

Narrow bands of Gaussian noise were computer-generated using a digital generation procedure detailed by Richards (1987). Forty different 500-ms samples of noise were generated by summing tones separated by 2 Hz. The amplitudes of the tones were chosen from a Rayleigh distribution, and the phases were chosen from a uniform distribution ranging from 0 to 2π rad. For each experimental session, a subset of these waveforms (between 5 and 10) was used. On each presentation, one of the waveforms was randomly chosen, and a 200-ms portion of the 500-ms waveform was drawn at random. For cases in which the interaural delay was smaller than the sampling period (40 μs), the delay was obtained by using waveforms digitally generated with the appropriate time delay (allowing the use of 5 or 10 μs interaural delays).

Stimuli were generated via a 2-channel, 16-bit digital-to-analog converter at a sampling rate of 25 kHz. The outputs of the D/A converter were low-pass filtered at 10 kHz (with an attenuation slope of approximately 110 dB/octave), and routed through programmable attenuators. Stimuli were presented via matched TDH 49 headphones mounted in circumaural cushions (MX-51) and driven in-phase. Within each channel, onset and ongoing interaural time delays were introduced digitally before the target and interferer bands were summed, digitally, prior to output. The targets and interferers were gated synchronously. Interaural level differences were produced by increasing the level to one ear and decreasing the level to the other ear by half the total ILD. Interaural level differences were introduced using programmable attenuators, and target and interferer bands were summed using an analog adder, with the exception of the random-interferer/across-cue condition in which interaural level differences were introduced by digital scaling.

D. Procedure

The first conditions run were the ITD-discriminations and ILD-discriminations when the target was presented in isolation (target alone) and when a diotic interferer was also present (diotic interferer). The order of data collection in these conditions was counterbalanced across observers. The next two conditions run were the ITD-discrimination in the presence of an interferer that had a randomized ITD and the ILD-discrimination in the presence of an interferer that had a randomized ILD (random-interferer/within-cue). The last conditions completed were the random-interferer/across-cue conditions, in which the ITD-discrimination occurred in the presence of an interferer with a randomized ILD, and the ILD-discrimination occurred in the presence of an interferer with a randomized ITD. In all random-interferer conditions (both within-cue and across-cue), the order of ITD or ILD discriminations was pseudo-random.

Observers completed 50 trials at each of three different levels of interaural disparity (ITD or ILD). The d' values at each level of interaural disparity were fitted to a line using a least-squares fit. Four replicates of the psychometric function were obtained in each condition. The average of the four values at which $d'=1$ yielded a threshold estimate for each condition, based on a total of 600 trials. The threshold estimates thus obtained were nearly identical to the estimates obtained by fitting a single line to all of the data for each observer; the mean thresholds were utilized because they were associated with an estimated standard error. For the target-alone and diotic-interferer conditions, the intercept was forced through zero based on the fact that zero disparity should correspond to chance performance on a lateralization task. For the random-interferer/within-cue and across-cue conditions, both the slope and intercept were estimated. This was because random draws of the interferer ITD (or ILD) might not have a mean of zero, so that we could not be certain *a priori* that a zero-valued intercept would underlie each fit.

Each interval began with a visual warning presented on a video monitor. The two intervals of a trial were separated by approximately 650 ms of silence. In one of the experimental conditions (the random-interferer/across-cue condition), increased computational requirements necessitated intervals that were separated by 880 ms of silence. Feedback was given after each trial on a video monitor, and the percent correct obtained was displayed after the completion of 50 consecutive trials (a block). Each block of 50 trials began with practice trials, which were terminated by the subject when ready.

E. Observers

The four observers were students at the University of Pennsylvania, ranging from 17 to 27 years of age and all of

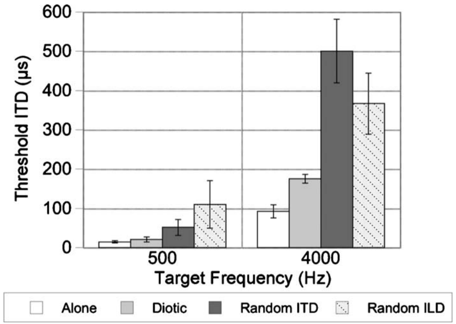

FIG. 1. Averaged threshold ITDs in μs for 500-Hz (left) and 4000-Hz (right) targets. The interferer conditions, from left to right within each panel, are indicated with shading: target-alone (unfilled), diotic (light shading), random ITD (dark shading), and random ILD (striped). Error bars indicate the standard error of the mean across the four observers.

normal hearing. Three subjects were paid for their time and were inexperienced in psychophysical tasks. Observer 4 (the first author) was experienced with similar lateralization tasks. Orientation of the naive observers to the lateralization task required approximately 9000 practice trials before asymptotic performance was reached.

Additionally, a minimum of 300 practice trials was required prior to collecting data in a novel condition.

III. RESULTS

Figures 1 and 2 display the average results across listeners, which are representative of the patterns displayed by individuals. In this section, the results of individual observers are subjected to one-tailed t-tests whereas the results pooled across observers are tested by either t-tests or ANOVAs that treat observers as a random factor.

A. Targets discriminated on the basis of ITDs

Figure 1 shows the ITD thresholds in microseconds for the target-alone condition (unfilled bars) and the diotic-interferer condition (lightly shaded bars). For Fig. 1, and all subsequent figures, the data obtained using the 500-Hz target are plotted on the left, and the data obtained using the 4000-Hz target are on the right. Error bars indicate the standard error of the mean across observers.

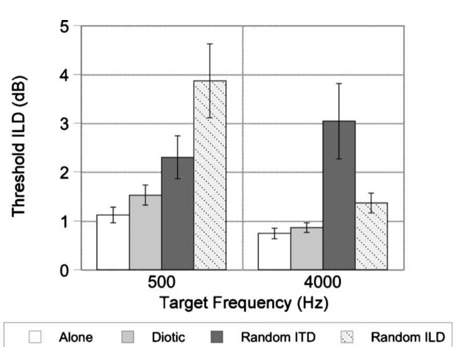

FIG. 2. Averaged threshold ILDs in dB for 500-Hz (left) and 4000-Hz (right) targets. The interferer conditions, from left to right within each panel, are indicated with shading: target-alone (unfilled), diotic (light shading), random ITD (dark shading), and random ILD (striped). Error bars indicate the standard error of the mean across the four observers.

On average, ITD threshold for a 500-Hz target was 15 μs when the target was presented alone and increased to 21 μs when a 4000-Hz diotic interferer was present. ITD threshold for a 4000-Hz target was 92 μs when the target was presented alone and increased to 175 μs when a 500-Hz diotic interferer was present. Consistent with the averages, each observer obtained larger thresholds in the diotic-interferer condition than in the target-alone condition, for both target frequencies. Only Obs. 3 displayed a significant increase in ITD threshold for a 500-Hz target in the presence of a 4000-Hz interferer [$t'(5.5)=3.27$, $p<0.025$ one-tailed t-test for heterogeneous variances[1]]. However, all four observers' ITD thresholds for a 4000-Hz target increased in the presence of a diotic 500-Hz interferer [$t'(3.4)=6.5$, $p<0.005$; $t'(5.2)=2.2$, $p<0.05$; $t'(3.1)=4.3$, $p<0.025$; $t'(4.3)=5.6$, $p<0.005$; Obs. 1–4 respectively].

The dark bars in Fig. 1 plot the ITD threshold in microseconds for the random-interferer/within-cue condition (i.e., in which the interferer ITD was randomly varied across intervals). The average ITD threshold for a 500-Hz target was 52 μs, while the average ITD threshold for a 4000-Hz target was 501 μs. For each observer, randomization of the interferer ITD resulted in higher thresholds than those which were obtained in the diotic-interferer condition. The increase in threshold for the 500-Hz target was significant for Obs. 1, 2, and 3 [$t'(4.5)=3.9$, $p<0.01$; $t'(3.5)=3.8$, $p<0.025$; $t'(3.6)=5.1$, $p<0.005$, respectively] and the increase in threshold for the 4000-Hz target was significant for all observers [$t'(3.2)=4.6$, $p<0.01$; $t'(4.2)=9.7$, $p<0.001$; $t'(3.2)=3.5$, $p<0.025$; $t'(5.1)=2.1$, $p<0.05$; Obs. 1–4, respectively].

The striped bars in Fig. 1 display the averaged ITD threshold in microseconds for the random-interferer/across-cue condition, in which the ILD of the interferer was randomized across intervals. Randomization of the interferer ILD resulted in higher thresholds than when the interferer was diotic, yielding average ITD thresholds of 110 μs for a 500-Hz target and 367 μs for a 4000-Hz target. ITD thresholds for a 500-Hz target were higher when the 4000-Hz interferer had a randomized ILD than when it was diotic for Obs. 1, 2, and 3 [$t'(3.1)=2.8$, $p<0.05$; $t'(4.1)=8.9$, $p<0.001$; $t'(3.0)=5.4$, $p<0.01$, Obs. 1–3 respectively]. ITD thresholds for a 4000-Hz target were higher when the 500-Hz interferer had a randomized ILD than when it was diotic for Obs. 1, 2 and 3 [$t'(5.1)=5.4$, $p<0.005$; $t'(3.3)=4.5$, $p<0.01$; $t'(5.2)=6.5$, $p<0.001$, Obs. 1–3 respectively].

Caution should be used in comparing the interfering effects of the two types of random interferers, within-cue and across-cue, because it is not clear how to define a comparable range of randomization across the ITD and ILD domains (although a 10 dB ILD and 500 μs ITD should produce reasonably similar extents of laterality). Given this caveat, the threshold increase over the diotic-interferer condition was greatest for low-frequency targets when the ILD of the high-frequency interferer was randomized, whereas it was greatest for the high-frequency targets when the ITD of the low-frequency interferer was randomized. This pattern was consistent across observers, as indicated by a significant interaction between target frequency and the type of interferer (random ITD or ILD) on the thresholds obtained in the random-interferer/within-cue and across-cue conditions [$F(1,3)=10.3, p<0.05$]. It appears that the most interference occurs when the cue randomized in the interferer is the one that is the most important in *its* frequency region.

B. Targets discriminated on the basis of ILDs

Figure 2 shows the averaged ILD thresholds in dB for the target-alone condition (unfilled bars) and for the diotic-interferer condition (lightly-shaded bars). Error bars show the standard error of the mean across observers. On average, ILD threshold for a 500-Hz target was 1.1 dB when the target was presented alone and increased to 1.5 dB when a 4000-Hz diotic interferer was present. ILD threshold for a 4000-Hz target was 0.7 dB when the target was presented alone and increased to 0.9 dB when a 500-Hz diotic interferer was present. Data from each observer were consistent with the averages. The threshold increase for the 500-Hz target was significant for Obs. 1, 3, and 4 [$t'(6.0)=2.1$, $p<0.05$; $t'(6.0)=2.8$, $p<0.025$; $t'(3.8)=2.3$, $p<0.05$, respectively]. For the 4000-Hz target, the threshold increase was significant only for Obs. 4 [$t'(5.9)=2.3, p<0.05$]. Pooling across the observers, ILD thresholds were significantly greater in the presence of a diotic interferer for both the 500 Hz [$t(3)=5.67, p<0.05$] and 4000-Hz targets [$t(3)=3.66, p<0.05$]. An analysis of variance that treated observers as a random factor and target frequency as a fixed factor did not indicate a differential effect of target frequency on the size of the threshold increase in the diotic-interferer condition over the target-alone condition, although the mean threshold increased more for the 500-Hz target than for the 4000-Hz target.

The striped bars in Fig. 2 represent the averaged ILD threshold in dB for the random-interferer/within-cue condition. The average ILD threshold for a 500-Hz target was 3.9 dB, while the average ILD threshold for a 4000-Hz target was 1.4 dB. With only one exception, for each observer and each target frequency, randomization of the interferer ILD resulted in higher threshold than did a diotic interferer. The exception was that Obs. 4's ILD threshold for a 4000-Hz target did not depend on whether the 500-Hz interferer was diotic or random. The threshold ILD for the 500-Hz target was significantly higher in the random-interferer condition than in the diotic-interferer condition for all four observers [$t'(3.3)=3.1$, $p<0.025$; $t'(3.2)=10.8$, $p<0.001$; $t'(3.6)=7.0$, $p<0.005$; $t'(5.9)=4.8$, $p<0.005$; Obs. 1–4, respectively]. For the 4000-Hz target, thresholds increased significantly for Obs. 1, 2, and 3 [$t'(3.3)=3.3$, $p<0.025$; $t'(4.3)=4.4$, $p<0.005$; $t'(5.7)=3.9$, $p<0.01$, respectively].

The dark bars in Fig. 2 display the averaged ILD threshold in dB obtained in the presence of an interferer with a randomly varying ITD (i.e., the random-interferer/across-cue condition). Randomization of the interferer ITD resulted in higher thresholds than those which were obtained when the interferer was diotic, yielding average ILD thresholds of 2.3 dB for a 500-Hz target and 3.0 dB for a 4000-Hz target. ILD threshold for the 500-Hz target was significantly higher when the ITD of the interferer was randomized than when it was diotic for Obs. 1 and 3 [$t'(5.0)=2.7$, $p<0.025$; $t'(4.4)=4.6$, $p<0.005$, respectively]. The threshold increase for the 4000-Hz target was significant for all four observers [$t'(3.2)=10.7$, $p<0.001$; $t'(3.1)=8.0$, $p<0.005$; $t'(3.2)=3.0$, $p<0.05$; $t'(4.8)=3.1$, $p<0.025$; Obs. 1–4, respectively].

Although the mean ILD thresholds for a 4000-Hz target appeared higher when the interferer had a randomized ITD, as opposed to a randomized ILD, and the mean ILD thresholds for a 500-Hz target appeared higher when the interferer had a randomized ILD, there was no significant interaction between the center frequency of the target and the type of interferer (random ITD or ILD) on the thresholds obtained in the random-interferer/within-cue and across-cue conditions (in an ANOVA that treated subjects as a random factor). This lack of significance may reflect the fact that the data from the random-interferer/across-cue condition exhibit the highest variability across observers.

C. Evaluation of the trial-by-trial effect of a random interferer

An additional analysis was done to determine whether the overall increase in thresholds due to the randomization of the interferer ITD or ILD could be better explained by a weighted combination model or by possibly deleterious effects of listener uncertainty.

Uncertainty due to randomization could produce, for example, increased internal noise associated with changes in criterion placement or an increased attention load. On the one hand, a weighted combination model predicts that the change in ITD (ΔITD) or the change in ILD (ΔILD) of the interferer across the two intervals of a trial should have a systematic influence on the observers' responses. On those trials in which the interferer ΔITD or ΔILD happens to be consistent in direction with the target ΔITD or ΔILD, the integration of interaural information across frequency channels would be expected to increase correct responses. However, on approximately 50% of the trials the interferer ΔITD or ΔILD opposes the direction of the target ΔITD or ΔILD and so integration across frequencies would reduce accuracy. On the other hand, if the threshold increases in the presence of a random interferer reflected a general uncertainty effect, then performance would be independent of the particular interferer ΔITD or ΔILD from trial to trial.

In order to assess the effect of the interferer on the observers' discrimination responses, trial-by-trial responses were analyzed as a function of the change in interferer ITD or ILD within a trial [an analysis similar to one performed by Massaro *et al.* (1976)]. For each observer, an analysis was performed on a set of 200 trials which had a fixed target ITD or ILD, using values which led to performance levels close to 76% correct. The percent correct was plotted as a function of the relative change in interferer ITD or ILD across the two intervals. In this analysis, the difference between the ITD (or ILD) of the interferer in intervals 1 and 2 was assigned a positive sign if it changed in the same direction as the target, and a negative sign if it changed in the opposite direction as

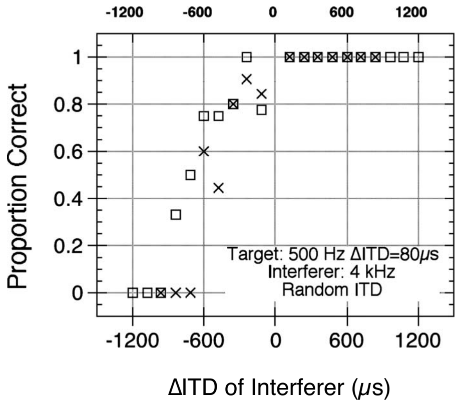

FIG. 3. The proportion of correct lateralization responses for the target is plotted as a function of the change in ITD of the interferer. Where the abscissa is negative, change in interaural disparity of the interferer was in the opposite direction to that of the target. Where the abscissa is positive, change in the interaural disparity of the interferer and that of the target were in the same direction. For this example (Obs 1), an 80 μs change in ITD was applied to the 500-Hz target. Trials in which the target led in the left (x) or right (□) ear during the first interval are plotted separately.

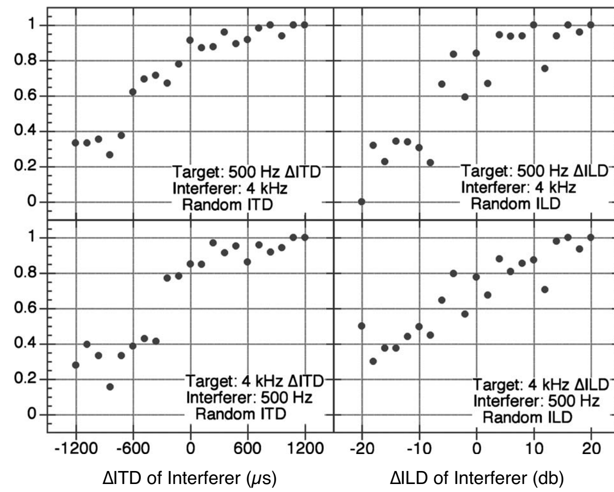

FIG. 4. The average proportion of correct lateralization responses for the target is plotted as a function of the change in ITD (left panels) or ILD (right panels) of the interferer. Upper panels are for the 500-Hz target, and lower panels are for the 4000-Hz target. In other respects, the plots are as described in Fig. 3.

the target. For example, if the interferer ITD led in the right ear by 40 μs on interval 1 and led in the same ear by 400 μs on interval 2, then the absolute value of the ΔITD of the interferer on that trial was 360 μs. If the target ITD was changed from left-leading to right-leading, the interferer ΔITD was assigned the value +360 μs because the target and interferer moved in the same direction. But, if the target ITD changed from right-leading to left-leading, then the interferer ΔITD was assigned −360 μs (i.e., in opposition to the target).

If responses were completely dependent upon the direction of change in the interferer ITD, the responses would be 100% correct when the interferer ΔITD changed in the same direction as the target (i.e., was positive), and would be 0% correct when the interferer ΔITD changed in the opposite direction from the target (i.e., was negative). If responses were independent of the interferer's direction, d' should have been 1.0 everywhere because that is the performance level in the diotic condition. Some alternative explanations for interference such as monaural interactions and listener uncertainty would predict no systematic effect of the ITD of the interferer. Figure 3 shows Obs. 1's percent correct (for a target ITD of 80 μs) as a function of the relative change of the interferer ITD. This plot is representative of the results for the other observers and the other conditions and shows that responses depended strongly on the interferer, even when the diotic condition does not produce measurable interference.

Figure 4 displays four panels, each with the same ordinate as Fig. 3, and each of which represents an average across all four observers within each random-interferer condition. Clockwise from the top left, the conditions are 500-Hz target ITD, 500-Hz target ILD, 4000-Hz target ILD, 4000-Hz target ITD. The data presented in Fig. 4 were obtained from the random-interferer/within-cue condition, but the data from the random-interferer/across-cue condition were similar. Relative to Fig. 3, the average data shown in Fig. 4 have shallower slopes. The reduction in slope is associated with the averaging of different functions for the different observers. Nonetheless, a clear dependence on the change in the interferer ITD (or ILD) is apparent in the averaged data. Figure 4 demonstrates that observers' ability to discriminate differences in the target ITD (or ILD) is systematically influenced by the magnitude and direction of the interferer ITD (or ILD).

IV. DISCUSSION

For ITD discrimination, the diotic low-frequency interferer produced robust interference effects, while the high-frequency interferer produced only a small, non-significant interference. These results are consistent with those of McFadden and Pasanen (1976), and support the notion that low frequency ITDs contribute more than high frequency ITDs to an across-frequency interaction. In contrast, for ILD discrimination, the high-frequency diotic interferers produced interference equal to or larger than the low-frequency diotic interferers. This finding is consistent with the results extracted from a subset of the control conditions used in a study of hearing impairment and interference (Smith-Olinde *et al.*, 1998, experiment one). When the ILD of the interferer was randomized, ILD thresholds were highest for low-frequency targets. Thus, the concept of low-frequency dominance applies to ITDs but does not generally characterize interference effects. Nor is the current data set readily explained by a peripheral interaction. Randomizing the ITD or ILD of the interferer increased the interference effect, and errors were systematically related to the change in interferer ITD or ILD on each trial. Indeed, had randomization not been employed, a different conclusion might have been reached regarding ILDs and low-frequency interference, because the magnitude of the interference effect was quite small in the diotic interferer condition. Finally, randomization of the interferer ITD when the target ILD was discriminated, or *vice-versa*, produced interference, showing that interference is not restricted to target/interferer pairs with the same type of interaural disparity (ITD or ILD). In fact, the pattern of results from the across-cue conditions support the idea that lateral position underlies the interference effects as opposed to a within-cue combination of binaural disparities.

We reach this conclusion by examining the asymmetric across-frequency patterns of interference between the ITD and ILD conditions. These patterns have implications for the weights in an across-frequency weighted combination model. The weighting as a function of frequency must vary according to the cue being discriminated: low frequencies contributing more than high frequencies for ITD discriminations, and high frequencies contributing equally to or more than low frequencies for ILD discriminations. On the whole, the data are consistent with the hypothesis that the relative contribution of different frequency regions and different interaural cues depends on the acuity with which the interaural disparities are encoded at each frequency region. This suggestion, in turn, implies that the weighting occurs on the basis of both frequency and interaural disparity (time and level differences).

The observed increase in threshold from the diotic to the random condition is also consistent with a combination of information across frequencies. This threshold increase is not accounted for by a general uncertainty effect, in which randomization of an irrelevant stimulus parameter would lower overall performance but would not generate responses that depended systematically on the interferer ITD or ILD from trial to trial. Figures 3 and 4 illustrate that the observers' responses depend on information accumulated across both frequency and interaural cues. The fact that the psychometric function increases monotonically as a function of the change in the interferer's ITD across intervals (Fig. 3) indicates that the interferer systematically influenced responses, and helps to reject possible alternative explanations for the increased interference caused by the randomization. Because the task was a two-interval forced-choice task, zero proportion-correct performance means that responses are consistently incorrect (i.e., d' is very large, but negative). This rules out a simple probabilistic mixing model in which the observer attended to the interferer location on some fixed percent of the trials (e.g., 20%). Such a model would, in fact, predict an elevation in threshold due to randomization, but it would predict that the function would asymptote at 20% correct rather than 0% on the left-hand side of the ordinate. This is because, on 20% of the trials, the observer should attend to the target and be correct even though the interferer ITD opposes the target. Second, this trial-by-trial analysis rules out an account based on listeners selectively attending to one spatial location (rather than one frequency channel). Such an account would predict that interference would be greater when the target and interferer have similar locations. If observers could narrow their selective attention to the central region indicated by the target (e.g., Drennan *et al.*, 2003), they would find it easier to ignore distracters with more lateralized positions and therefore should show a fall-off in interference at the extreme ends of the function. The monotonic psychometric function in Fig. 3 is inconsistent with this selective attention account.

Examining the qualitative pattern of threshold elevations[2] across both ITD and ILD targets, the effect of a 500-Hz interferer was always largest when the interferer ITD was randomly varied, while the effect of a 4000-Hz interferer was always largest when the interferer ILD was randomly varied. Of course, the magnitude of this effect would certainly depend upon the range of randomization used. For example, if the range of ITD randomization had been only 40 μs, the overall pattern would have shown that interferers with random ILDs always produced the greatest interference effect. However, the mere existence of interference in the random-interferer/across-cue condition, regardless of the relative magnitudes of the interference, establishes that the ITD and ILD domains can interact, even when a more optimal strategy would be to keep them separate. This interaction across frequency regions supports the idea that lateral position, rather than within-cue interaural disparities, is combined to produce the interference effect. This view is also consistent with models that implicate an interaction between ITD and ILD for producing a lateral position (e.g., Stern and Colburn, 1985) or deriving relative weights (e.g., Macpherson and Middlebrooks, 2002).

A. Application of a weighted combination model

Next we consider potential models in which interaural information is integrated across frequencies. As expected based on the results of Heller and Trahiotis (1996), a disparity-based weighted combination model that does not include lateral position fails to predict the amount of interference observed in this study. Threshold predictions for a disparity-based model were made using Eq. (A1) presented in the Appendix, following Heller and Trahiotis (1995). This equation predicts a much higher threshold for a 4000-Hz ITD target (571 μs predicted, vs 175 μs obtained), and it also predicts a high threshold for a 500 Hz ILD target (2.05 dB predicted, vs 1.4 dB obtained). Buell and Hafter (1991) note this discrepancy between their model and the data of McFadden and Pasanen (1976) in their Footnote(2). Conversely, it closely predicts the thresholds for the two conditions with comparatively less interference: the low-frequency ITD target (15 μs predicted vs 21 μs obtained) and the high-frequency ILD target (0.8 dB predicted vs 0.9 dB obtained).

One potential problem with a disparity-based model in accounting for data across disparate frequency regions is the assumption that interaural disparities, rather than lateral positions, form the decision variable.[3] Such models would attribute the differences in target-alone thresholds across the 4000-Hz and 500-Hz regions exclusively to a difference in internal variance by assuming that the change in mean produced by an ITD is the same across all frequency channels. According to a lateral-position based model, this assumption causes the disparity-based model to predict interference effects that are too large because it overestimates the variance in the 4000-Hz region relative to the 500-Hz region. In contrast, a lateral-position model attributes the elevated ITD thresholds for stimuli in the 4000-Hz region to two factors: (a) A greater extent of laterality is needed in the high frequency region due to its higher positional variance, and (b) it takes a greater ITD to achieve that lateral position. When the increased threshold for 4000-Hz tones is partially attributed to laterality and partially to variance, the estimated variance of the 4000-Hz region is reduced relative to the disparity-based model (although it is still estimated to be greater than the variance in the 500-Hz region). The result of a reduction in the estimated variance at 4000 Hz is an increase in the estimated weight attributed to that region, with the end result being that a lateral-position-based model predicts less high-frequency interference than does a disparity-based model. For example, Heller and Trahiotis (1996) used their lateral-position based model to estimate the standard deviations (sigmas) associated with the lateral positions of their stimuli. They measured the slopes of the functions relating ITD to lateral position in various frequency regions and estimated that the sigma in the 4000-Hz region was, on average, only a factor of 2.4 times larger than the sigma in the 500-Hz region, whereas a disparity-based model would have predicted a factor of 6.0.

It is possible that the amount of interference reported in our paper could be well-predicted by a lateral position model. A precise test of the laterality-based model would require the use of measures of the lateral positions of these stimuli from the four subjects used in this study, but unfortunately such data are not available. However, it is possible to garner rough estimates of lateral position from the Heller and Trahiotis (1996) study (with the caveat that they used different stimuli) which reported that the slope of the function relating ITD to lateral position was, on average, a factor of 2.58 greater for the 500-Hz region than for the 4000-Hz region. This information about lateral position, in combination with the target-alone ITD thresholds reported herein, can be combined to predict thresholds under conditions of interference via Eq. (A2) in the Appendix [identical to Heller and Trahiotis's (1996) Eq. A9]. The laterality model embodied by Eq. (A2) predicts that the threshold ITD for a 4000-Hz target with a diotic 500-Hz interferer will be 237 μs, only 62 μs larger than the obtained threshold of 175 μs. Recalling that the disparity-based model predicted a threshold of 571 μs, it is evident that the use of the lateral position model reduces the discrepancy between the predicted and observed thresholds by more than a factor of 6 relative to the disparity based model (62 μs vs 396 μs). Although additional predictions cannot be made in a similar manner for all of the ITD and ILD thresholds reported here, this example illustrates the benefits of a model of binaural interference based on lateral position.

V. CONCLUSIONS

The results reported here are qualitatively consistent with previous results that demonstrate interference effects on lateral position (Heller and Trahiotis, 1996; Best *et al.*, 2007). Our experiments, which examined the discrimination of interaural cues for low- and high-frequency bands of noise, indicate that the relative contribution of ITD and ILD cues depends on frequency. For ITD discrimination, interference was greater for 4000-Hz targets, but for ILD discrimination, there was little difference in interference across frequency. An interferer which has an ITD or ILD that is randomly chosen on each interval is more disruptive than a diotic interferer, revealing that interference can be sizable not only for high-frequency targets but also for low-frequency targets with high-frequency interferers. Because interference effects were obtained when the target to be detected varied in ILD or ITD and the interferer varied in ITD or ILD, respectively, it is apparent that information associated with ITDs and ILDs interact across frequency, at least when both ITDs and ILDs vary across trials. The overall pattern of thresholds with and without interferers is consistent with an explanation based on a lateral position model.

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APPENDIX: BASIS FOR WEIGHTED COMBINATION OF DISPARITY-BASED PREDICTIONS

The combination rule proposed by Buell and Hafter (1991) for ITD discrimination assumes that there exist combination weights associated with the interaural time information that are inversely proportional to the variance of each frequency channel, and that when $d'=1$, σ is equal to $\Delta\mu$, which is estimated by the ITD threshold of the target in isolation in that frequency region. Therefore, the weight in each frequency region is inversely proportional to the square of the ITD threshold in that region. For the current application, the interaural cue can be either time or level differences, with different weights associated with each cue across the different frequency channels. For example, let THRESH ITD_T be the ITD threshold for a 500-Hz target presented alone and let THRESH ITD_I be the ITD threshold for the 4000-Hz interferer.

Following Heller and Trahiotis (1995), using a disparity-based (not position-based) model, a prediction of the ITD threshold for a target presented simultaneously with a diotic interferer is given by

$$\text{THRESH ITD}_{T+I} = \text{THRESH ITD}_T \sqrt{1 + \frac{\text{THRESH ITD}_T^2}{\text{THRESH ITD}_I^2}}, \qquad \text{(A1)}$$

whereas for a lateral position model, if the slope of the function relating stimulus ITD to laterality is s, then

$$\text{THRESH ITD}_{T+I} = \text{THRESH ITD}_T \sqrt{1 + \frac{[s_T \text{THRESH ITD}_T]^2}{[s_I \text{THRESH ITD}_I]^2}}. \qquad \text{(A2)}$$

[1]The t' test is a t-test that conservatively compares means which have unequal variances by pooling the variances and adjusting both the degrees of freedom and the critical value of t. The denominator of the t' statistic is the square root of the sum of the variances of the two means being compared, and the degrees of freedom are approximated according to Welch's (1938) formula. The comparison of thresholds within individual subjects required a t' test because the standard deviations were larger for thresholds obtained in the presence of an interferer than for the target alone. The t' test for interference was one-tailed because the prediction was explicit as to the direction of the change: Threshold would increase in the presence of an additional band of noise.

[2]The discussion in this paragraph describes the pattern of mean thresholds, but the difference between means was not necessarily significant within or across observers in each random-interferer/across-cue condition. (Details about statistical significance are provided in the Results section.)

[3]Some previous studies that have examined interference with an ITD-detection task, in which only one interval contains an ITD and the other is diotic, may permit interaural correlation or image variance to be used as a cue because the interaural correlation is highest for the diotic interval. Because the present experiment used a two-interval task in which an equal and opposite ITD was presented to the target on the two intervals of a trial, it is possible to claim that discrimination was based on changes in lateral position.

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