Binaural interference in the free field^{a)}

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In an anechoic chamber the minimum audible angle (MAA) was measured in seven normal-hearing adults for a narrow band of noise centered at 4000 Hz (target). In the absence of an interfering stimulus, the average MAA was 2.1°. When a low-frequency interferer (a narrow band of noise centered at 500 Hz) was pulsed on and off with the target from directly in front of the subject, the average MAA was significantly elevated (13.4°). However, if the interferer was continuously present, or if it consisted of two independent noises presented from $\pm 90^\circ$, interference was much reduced. The interference effect was asymmetric: a high-frequency interferer did not result in elevation of MAA threshold for a low-frequency target. These results are similar to those that have been extensively reported for stimuli under headphones [Bernstein and Trahiotis (1995). *J. Acoust. Soc. Am.* **98**, 155–163]. These data are consistent with the notion that interference from a spectrally remote low-frequency interferer occurs in the free field to the extent that the target and interferer are fused into a single perceptual object. If cues are provided that promote perceptual segregation (such as temporal onset differences or spatial location differences), the interference is reduced or eliminated. © 2010 Acoustical Society of America. [DOI: 10.1121/1.3311862]

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I. INTRODUCTION

Binaural interference refers to the detrimental effect of one stimulus (“interferer”) on performance in certain binaural tasks involving a second stimulus (“target”), where the target and interferer are generally well separated in frequency. Most typically, the effect is observed when the task is to detect interaural time differences (ITDs) in a high-frequency complex signal in the presence of a low-frequency interferer that has zero ITD (i.e., is presented diotically). For example, the threshold ITD for a sinusoidally amplitude-modulated (SAM) 4000-Hz tone may be elevated in the presence of a simultaneously presented diotic SAM 500-Hz tone, relative to when measured in isolation (Heller and Trahiotis, 1995b). Binaural interference effects have also been reported when the task is to detect interaural level differences (ILDs) (Bernstein and Trahiotis, 1995; Heller, 1992), to detect high-frequency binaural signals in the presence of masking noise (Bernstein and Trahiotis, 1995), or to judge the laterality of high-frequency complex tones (Heller and Trahiotis, 1996). Best *et al.* (2007) provided a comprehensive review of various experiments that have reported binaural interference over the past 30 years.

Since the interferer and target stimuli in most of these studies are spectrally remote from each other, binaural inter-

ference cannot be attributed to energetic masking effects occurring within single frequency channels. Rather, the general explanation for the effect is based on the notion that when a target and interferer are presented simultaneously, subjects form an “obligatory combination” of the two stimuli, such that the subject is not able to hear out the relevant information in the target. Thus, the cue information in the target stimulus (e.g., the ITD) is “diluted” by the irrelevant or zero ITD information in the interferer, and the resultant ITD threshold is elevated. Quantitative “weighted-combination” models based on this notion have been reasonably successful in describing the interference observed in some experiments (Buell and Hafter, 1991; Heller and Trahiotis, 1996).

Several additional interesting aspects of binaural interference have been reported. First, the effect is asymmetric, at least when the task is ITD detection. That is, a low-frequency interferer may disrupt ITD processing of a high-frequency target, but the reverse effect (interference by a high-frequency interferer on the ITD processing of a low-frequency target) has not been observed (e.g., McFadden and Pasanen, 1976). On the other hand, the interference effect is fairly symmetric for ILD detection. That is, there is a similar degree of interference from a high-frequency diotic interferer on low-frequency ILD detection as in a reverse situation (Heller and Richards, 2010). The weighted-combination models mentioned in the previous paragraph would predict these effects for both ITD and ILD tasks. In the case of ITD detection, the models accord more weight to the low- than the high-frequency stimuli when the two signals are combined (due to lower ITD thresholds and steeper laterality slopes for low- than high-frequency targets when measured

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in isolation; Heller and Trahiotis, 1996). This leads to a prediction of asymmetric interference in the observed direction. In the case of ILD detection, the models would accord similar weights to low- and high-frequency stimuli, since ILD thresholds in isolation are similar across a wide frequency range (e.g., Mills, 1960), leading to the correct prediction of no asymmetry for this task.

The second effect that has been consistently observed is that binaural interference is greatly reduced, or sometimes eliminated, when the interferer is presented continuously, compared to when pulsed on and off with the target (Bernstein and Trahiotis, 1995; Heller and Trahiotis, 1995b). One explanation for this finding is that the relative timing of the target and interferer determines whether the combined signal is perceived as one or two auditory objects (Woods and Colburn, 1992; Best *et al.*, 2007). When the target and interferer are pulsed on and off together, they tend to be perceived as a single object, and there is an obligatory combination of the cue information from the two frequency regions, as described above. However, if the target is gated on and off in the presence of a continuous interferer, the two signals are generally perceived as two separate objects. In this case, there is no longer an obligatory combination of information across the two frequency regions, allowing the subject to attend analytically to the target stimulus and obtain a threshold similar to that obtained in isolation.¹

The third finding is that the interaural configuration of the interferer sometimes affects the amount of interference. One might expect that any interaural manipulation that tended to place the interferer in a different lateral position from that of the target might promote segregation of the two signals, and thus, result in less interference. This was indeed the direction of results in a study by Trahiotis and Bernstein (1990), who found, using broadband interferers, that a pulsed uncorrelated interferer (having a diffuse lateral image) resulted in less interference than a pulsed diotic interferer (having the same lateral position as that of the target). However, this result has not generally been observed. For example, in a study that was confined to ITD detection in low-frequency tones, Buell and Hafter (1991) did not find an effect of the ITD of the interferer. That is, the degree of interference on the ITD detection of a target tone was independent of the ITD (and presumably, therefore, of the perceived lateral position) of the interferer tone. In another study, Buell and Trahiotis (1993) found that a 2-kHz interferer produced *more* interference for a 4-kHz target when the interferer and target were in different lateral positions, compared to when the two signals shared a common lateral region. Similarly, Bernstein and Trahiotis (1995) found that an interaurally uncorrelated interferer usually produced more interference than a diotic interferer, even though the latter interferer would be more similar to the target in terms of perceived lateral position.

The studies cited in the previous paragraph all involved detection tasks (specifically, ITD detection). It is noteworthy that in experiments that have measured *lateralization* of high-frequency targets (Heller and Trahiotis, 1996; Best *et al.*, 2007), the degree of “pulling” exhibited by a low-frequency interferer *increases* as target-interferer spatial separation increases (although the percent of lateral position

change stays relatively constant). From this perspective, one could conclude that in a lateralization task, interference increases or does not change with spatial separation (depending on whether one considers the absolute or proportional change in lateral position as the appropriate measure of interference).

In summary, the effects of the interaural configuration of the interferer on the amount of interference are mixed and are not well understood. However, the fact that the interaural configuration of the interferer affects the amount of interference at all (in either direction) supports the notion that the threshold elevation observed in the detection experiments is not attributable to interference in *monaural* channels (Trahiotis and Bernstein, 1990; Bernstein and Trahiotis, 1995; see also Heller and Trahiotis, 1995a).

Finally, the fourth result that has characterized the studies of binaural interference is the large inter-individual variability observed (Woods and Colburn, 1992; Heller and Trahiotis, 1995b; Best *et al.*, 2007). These intersubject differences may reflect differences in the degree to which subjects are able to “listen analytically,” i.e., the degree to which the combination of information across frequency regions is indeed “obligatory.” The differences may also reflect the application of different listening strategies when faced with a task involving complex stimuli.

Binaural interference has typically been investigated only under headphones. The only study we are aware of that has investigated interference using full spatial cues (simulating free field presentation) was a study of virtual horizontal-plane localization, using narrow bands of noise centered at 500 and 4000 Hz that were convolved with head-related transfer functions measured from the Knowles Electronic Manikin for Acoustic Research (KEMAR) (Smith-Olinde *et al.*, 1998). Interestingly, these investigators found that normal-hearing subjects had similar error scores whether the target band of noise (high or low) was presented in isolation or when it was presented in the presence of a pulsed interferer band (low or high, presented either from a random or fixed location). In other words, there was no evidence of interference in this virtual localization task among the normal-hearing subjects.²

In the present study, we investigated some of the above-mentioned aspects of binaural interference in the free field, employing parallel procedures to those used in the headphone studies. Instead of measuring localization accuracy, we measured the minimum audible angle (MAA), a task analogous to the headphone studies of sensitivity to interaural differences for stimuli presented near midline. Specifically, we measured the MAA for a high-frequency band of noise (target) in the absence or presence of a low-frequency band of noise (interferer). It should be noted that this adaptation of the study of binaural interference to the free field necessarily changes the relevant cues for spatial processing. Spatial resolution for the target (high-frequency) stimulus will be governed by ILD cues, while that for the interferer (low-frequency) stimulus will be governed by ITD cues (e.g., Mills, 1960; Wightman and Kistler, 1992). Nevertheless, we found some parallels between the interference results in the free field and the ITD detection results obtained under head-

phones. In particular, we found significant interference when the low-frequency interferer was pulsed on and off with the target, but not when it was presented continuously. We found no interference when the target was the low-frequency stimulus and the interferer was the high-frequency stimulus (i.e., there was asymmetry). On the other hand, in contrast to Buell and Trahiotis (1993), and Bernstein and Trahiotis (1995), the interference produced by the low-frequency interferer on spatial resolution of the high-frequency target was considerably reduced when the interferer was composed of two stimuli, both spatially separated from the target. This result is more similar to the findings of Trahiotis and Bernstein (1990), in which an uncorrelated interferer produced less interference than a diotic interferer.

II. METHOD

A. Subjects

Subjects were seven normal-hearing adults, aged 25–31 (six female, one male). Each was tested in four to eight sessions, with each session lasting about 1 h. The first one or two sessions were considered practice, and data from these sessions were not included in the final data set. One female subject dropped out of the experiment early, so some of the means reported (see below) are based on six rather than seven subjects.

B. Environment and stimuli

All testing was conducted in the Bill Wilkerson Center anechoic chamber, with internal dimensions (measured between wedge tips) $4.6 \times 6.4 \times 6.7 \text{ m}^3$, and with a low-frequency cutoff of 100 Hz. A horizontal circular array of 64 loudspeakers (RCA 40-5000), with a diameter of 3.9 m and spanning a full 360° , was positioned in the chamber. The subject was seated such that his/her head was in the center of and in the same plane as the array of loudspeakers.

As described below, the interferer stimulus, when present, was presented either from a single loudspeaker directly in front of the subject, or, in one condition, from two loudspeakers located at $\pm 90^\circ$ azimuth. The target stimulus was presented from various azimuths (around a reference azimuth of 0°) on different trials, depending on the subject's performance and the particular azimuths required by the threshold tracking during a run. To present the target from an arbitrary azimuth (if a loudspeaker happened not to be at this azimuth), two loudspeakers on either side of the desired azimuth were activated with the target stimulus, with the respective levels selected to produce a virtual image at the designated azimuth (Pulkki and Karjalainen, 2001).³

Two stimuli were employed, each playing the role in different conditions of target and interferer. The high-frequency stimulus was a 400-Hz wide band of noise centered at 4000 Hz with filter skirts of 51 dB/octave or greater on both sides. The low-frequency stimulus was a 400-Hz wide band of noise centered at 500 Hz, with filter skirts of 48 dB/octave or greater on both sides.⁴ These center frequencies and bandwidths were selected to correspond to those employed by Bernstein and Trahiotis (1995) in their study of binaural interference under headphones. Each stimulus was

presented at a nominal level of 70 dB sound pressure level (SPL), as measured at the position of the subject's head, although a random level rove of $\pm 2.5 \text{ dB}$ was applied to each signal presentation to discourage the use of loudness cues. Stimulus levels were adjusted, as necessary, to compensate for individual loudspeaker differences, thereby ensuring that levels were equated for the two stimuli and were constant across loudspeakers.⁵ Stimulus duration (when not continuous) was 150 ms.

C. Procedure

1. Baseline conditions

The basic task involved measurement of the MAA for both the low- and high-frequency stimuli. In these two baseline conditions (one for each stimulus), the measurement was made without an interferer present. On each trial, the subject was presented with two sequential signals, symmetrically placed around the reference azimuth (0°). Duration of each presentation was 150 ms (20-ms rise-decay time), and the interstimulus interval was 700 ms. The subject's task was to respond whether the sequence appeared to go "left-right" or "right-left," and he/she recorded his/her response via a hand-held keypad. Feedback was not provided.

A three-down, one-up tracking rule was employed, which tracked the 79% performance level (Levitt, 1971). Specific terms of the staircase method varied among subjects and conditions to the extent that initial MAA values and initial and final stepsizes were chosen based on subject performance. For instance, subjects who had very high MAA thresholds on previous runs were given higher stepsize values to allow for completion of runs in a reasonable time frame. Similarly, subjects with very low MAA thresholds were given smaller stepsize values to allow for tracking down to accurate thresholds. The spatial separation of the two signals on the first trial was chosen to be well above threshold (e.g., about $5\text{--}8^\circ$ in the baseline condition). After three successive correct responses, the separation was decreased, and after each incorrect response, the separation was increased. The stepsize for these changes was reduced after two reversals in the tracking run. Initial and final stepsizes were selected to be appropriate for the particular condition being run. For example, for the baseline conditions, they were typically 2° and 1° . Stepsizes ranged from 0.5° to 4° in all conditions.

The tracking continued until there were a total of eight reversals, and the threshold MAA for a given run was computed as the mean of the last six of these reversal azimuth separations. Over the course of the experiment, four to eight runs were completed in each condition, and the final values reported were taken as the mean of all four to eight threshold estimates obtained.

2. Interferer conditions

In addition to the baseline conditions, MAAs were also measured in the presence of various interferers. The same procedure as described above was followed, except an interferer stimulus was also presented during the threshold run. A total of four interferer conditions were chosen, based on pilot

work. These included three low-frequency interferers for the high-frequency target and one high-frequency interferer for the low-frequency target.

- a. *PI 0°: low-frequency pulsed interferer (high-frequency target)*. In this case a low-frequency interferer was presented co-temporally with the high-frequency target. That is, it was pulsed on and off twice during the trial, corresponding to the two target presentations. The interferer was presented from 0° azimuth in both intervals of the trial.
- b. *CI 0°: low-frequency continuous interferer (high-frequency target)*. In this case the low-frequency interferer at 0° azimuth was turned on before the first trial of the run, and remained on continuously until the run had completed, and a threshold had been estimated.
- c. *PI ±90°: low-frequency pulsed interferer presented from the sides (high-frequency target)*. In this case the interferer consisted of two independent low-frequency noise bands. These two noises were pulsed on and off, co-temporally with the high-frequency target, from loudspeakers at ±90° azimuth.
- d. *PI 0°—High: high-frequency pulsed interferer (low-frequency target)*. This condition was parallel to condition (a), where a high-frequency interferer was presented co-temporally with the low-frequency target, and was always presented from 0° azimuth in both intervals of the trial.

As with the baseline conditions, four to eight runs were completed in each of the interferer conditions, and the final values reported were taken as the mean of all four to eight threshold estimates obtained. The order of conditions was pseudo-random for each subject, with the exception that the first threshold run for all subjects was a baseline MAA. Generally, after completing a run for a particular condition, a different condition was selected for the next run (i.e., the four to eight runs obtained for each condition were spread out over the multiple sessions that each subject completed).

III. RESULTS AND DISCUSSION

Results are displayed in Fig. 1, with the six conditions plotted along the abscissa. Means across subjects are shown as the large filled squares, and standard deviation bars are shown for those cases in which the standard deviations were larger than the symbol size. Individual thresholds are shown for the condition that demonstrated the largest variability (PI 0°).

A. High-frequency target

The data for the four conditions run with the high-frequency target are shown in the left panel in Fig. 1. A single-factor repeated-measures analysis of variance (ANOVA) revealed a significant effect of condition [$F(3,15)=10.18$; $p=0.04$, Greenhouse–Geisser correction applied]. Follow-up paired-sample *t*-tests are presented in Secs. III A 1–III A 4.

FIG. 1. MAA thresholds for all six conditions. Means across subjects are shown as the large filled squares, and error bars indicate one standard deviation (not shown when smaller than the data symbol). Left panel: target was a band of noise centered at 4000 Hz and the interferer was a band centered at 500 Hz. Right panel: target was a band of noise centered at 500 Hz and the interferer was a band centered at 4000 Hz. Data for the seven individual subjects are shown as the small filled circles in the PI 0° condition, 4-kHz target (see text for details). Conditions indicated along abscissa: BASE: baseline condition, no interferer; CI 0°: continuous interferer presented from 0° azimuth; PI 0°: pulsed interferer presented from 0° azimuth; PI ±90°: pulsed interferer presented from ±90° azimuth.

1. The effect of a low-frequency interferer

The mean no-interferer MAA (“BASE”) was 2.1°, which is in line with previous measures obtained with high-frequency stimuli (Mills, 1958; Hafter *et al.*, 1988, 1992). Follow-up paired-sample *t*-tests revealed that each of the three interferers resulted in significantly higher thresholds than the BASE condition. For the continuous interferer (“CI 0°”) the mean MAA was 2.4° [$t(6)=2.73$; $p=0.034$]; for the pulsed center interferer (“PI 0°”) the mean MAA was 13.4° [$t(6)=3.36$; $p=0.016$]; and for the interferer pulsed from the sides (PI ±90°), the mean MAA was 3.1° [$t(5)=3.64$; $p=0.015$]. Although each of the interferers thus had an effect on spatial resolution, the pulsed (center) interferer clearly had the most dramatic effect on performance, resulting in an average six-fold increase in the MAA (however, see discussion of individual differences below). By contrast, the CI 0° interferer produced an average increase in MAA of only 14%, and the PI ±90° produced an average increase of 48%.

2. The effect of interferer timing

The difference between the CI 0° and the PI 0° conditions was statistically significant [$t(6)=3.23$; $p=0.02$]. This finding is similar to the interference results typically reported for headphone-presented stimuli. For example, Bernstein and Trahiotis (1995) found that ITD and ILD thresholds for high-frequency noise bands were both elevated more in the presence of pulsed low-frequency interferers than in the presence of continuous low-frequency interferers. However, it is noteworthy that these investigators found a greater degree of interference with the continuous interferers than found in this study. In the conditions most similar to those of the present study, thresholds were elevated over the baseline conditions by 45% and 25% for ITD and ILD tasks, respectively, whereas thresholds in the current study were elevated only

by 14%. The effectiveness of grouping to reduce interference (e.g., [Best et al., 2007](#)) may be stronger with free field stimuli than with headphone-presented stimuli, possibly due to the externalization of the sounds and the availability of multiple cues.

3. The effect of interferer location

The difference between the PI 0° and the PI ± 90° conditions was also statistically significant [$t(5)=3.13$; $p=0.026$], indicating that the spatial separation of target and interferer considerably reduced the magnitude of interference (from 11.3° to 1.0°).

These results are not consistent with the majority of headphone studies that have examined the effect of spatial separation of target and interferer in discrimination experiments. As reported in the introduction, only the study by [Trahiotis and Bernstein \(1990\)](#) obtained results consistent with the present results; they found greater interference when the interferer and target had the same interaural configuration than when they had different interaural configurations. Other studies either found no effect of spatial separation of target and interferer ([Buell and Hafter, 1991](#)), or they found that the interferer was *less* effective when the two signals were in the same general lateral region than when they had very different interaural configurations ([Buell and Trahiotis, 1993](#); see [Bernstein and Trahiotis, 1995](#), for two out of three of their subjects).

The reasons for these differences between the headphone studies ([Bernstein and Trahiotis, 1995](#); [Buell and Hafter, 1991](#); [Buell and Trahiotis, 1993](#)) and the present free field study are not clear. It has been shown that spatial cues (e.g., ITDs) by themselves do not generally promote strong segregation ([Culling and Summerfield, 1995](#); [Darwin and Hukin, 1999](#)), which could account for the range of different effects seen in the headphone interference studies. Possibly the effect of spatial separation in promoting sound source segregation is more robust with free field than with ITD- or ILD-based manipulations (e.g., [Drennan et al., 2003](#)).

4. Individual differences

MAAs in the pulsed interferer condition (PI 0°) varied widely across listeners, with individual thresholds ranging from 4.6° to >25°. Individual thresholds for the seven subjects are displayed along with the mean in [Fig. 1](#) to illustrate this wide variation.

Four of the subjects had stable and relatively low thresholds in this condition (4.6–8.7°). Although these were higher than their no-interferer thresholds (by 2.9–5.7°), their stable performance indicates that they apparently adopted a consistent strategy, and were able to extract reliable spatial cues from the combination of the high-frequency target and the low-frequency interferer.

The other three subjects had considerable difficulty with this condition. One (whose data point at 25° has an upward pointing arrow attached) was never able to do the task at all. This subject commented that she heard all signals coming from straight ahead in this condition and guessed the direction change in every trial. Of the six threshold runs for this

subject, three did not terminate, and the other three terminated spuriously at values >50°. We arbitrarily assigned a threshold of 25° to this subject for purposes of statistical testing.

A second subject (whose data point at 17.3° has a diagonal arrow attached) commented that sometimes she could hear directional changes in the target, but other times not. The reported threshold for this subject is based on the mean of four threshold runs that terminated normally, but does not take into account four other threshold runs that did not terminate or terminated spuriously at values >50°. Finally, the subject whose data point is shown at 24.2° is noteworthy because this mean value is based on four threshold runs with MAA estimates of 37.7°, 10.0°, 39.3°, and 9.7°. This subject also apparently could detect spatial cues some of the time, but not on a consistent basis, resulting in large intra-subject variability in this condition. It should be pointed out that all three of the subjects who had difficulty with the PI 0° condition performed stably and similarly to the other subjects in the other five conditions of the study.

This large degree of inter- and intra-subject variabilities has also been observed in the interference conditions in headphone studies (e.g., [Bernstein and Trahiotis, 1995](#); [Heller and Trahiotis, 1995b](#); [Best et al., 2007](#)). [Best et al. \(2007\)](#) observed that such inter-individual differences may relate to differences in subjects' abilities to listen "analytically" to complex signals, as well as their adoption of differing strategies to attempt to isolate and attend to the relevant portions of the signals. These investigators also suggested that listener exposure may affect subjects' ability to listen analytically; that is, that interference may decrease with sufficient practice with the task. In the present study, inspection of thresholds obtained across the course of the experiment showed no evidence of "learning" over the four to eight sessions run, although it cannot be ruled out that further exposure may have resulted in reduced interference.

B. Low-frequency target

For the low-frequency target, mean threshold in the BASE condition was 1.5° and mean threshold in the presence of a high-frequency interferer (PI 0° condition) was 1.6° (right panel in [Fig. 1](#)). These were not statistically different from each other [$t(5)=1.83$; $p>0.1$]. (These means were based on six rather than seven subjects, since one dropped out before running these conditions.)

Thus, the same asymmetry of interference is observed in the free field spatial resolution task as has been reported for the ITD task under headphones ([McFadden and Pasanen, 1976](#); [Zurek, 1985](#); [Trahiotis and Bernstein, 1990](#)). This asymmetry is especially noteworthy given the differences in level between the two stimuli.⁵ That is, the fact that the level of the low-frequency stimulus is estimated to be about 14 dB below that of the high-frequency stimulus at subjects' eardrums might lead one to expect the interference provided by the 500-Hz noise would be reduced while that provided by the 4000-Hz noise would be enhanced, relative to what would be measured for equal-SPL stimuli. Despite these level differences, the pattern of data was the same as that

observed with an ITD task under headphones: a robust interference effect with a low-frequency interferer and little or no interference with a high-frequency interferer.

It should be recalled that different cues probably underlie spatial resolution of high- and low-frequency stimuli in the free field. That is, ITDs are the primary cues employed to discriminate the spatial position of low-frequency stimuli, while ILD cues are dominant in spatial discrimination of high-frequency stimuli (Mills, 1960; Wightman and Kistler, 1992). Thus, we can conclude from the present free field results that, for pulsed interferers, a low-frequency interferer apparently disrupts ILD processing of high-frequency stimuli, but a high-frequency interferer does not disrupt ITD processing of low-frequency stimuli.

These results are qualitatively similar to those obtained under headphones in the only two interference studies we are aware of that have measured both ILD and ITD detections. Heller and Richards (2010) replicated previous results in showing little or no interference from a high-frequency interferer on ITD detection of a low-frequency target. On the other hand, both Heller and Richards (2010) and Bernstein and Trahiotis (1995) showed that a low-frequency diotic interferer produced significantly elevated ILD thresholds in a high-frequency target, a result consistent with the present data. However, it should be noted that the increase in threshold in both studies was smaller than that observed in the present study. Heller and Richards (2010) reported a 29% increase in ILD threshold, and Bernstein and Trahiotis (1995) reported increases near 100% (i.e., a two-fold increase) in the conditions most similar to those of the present study. By contrast, in the current study, the increase in MAA threshold due to the pulsed low-frequency interferer was more than six-fold (2.1° vs. 13.4°).⁶ This suggests that other factors than pure disruption of ILD processing may have played a role in the degraded free field spatial resolution for high-frequency targets in the presence of low-frequency interferers. Possibly for signals that are externalized, spatial coincidence of target and interferer results in stronger grouping than for signals presented under headphones, leading to reduced ability to extract spatial information from the target. This would be consistent with our finding of a great degree of “release” from interference when target and interferer are spatially separated. As indicated above, this release is not consistently observed in the headphone studies.

It has been suggested that the basis for the asymmetric direction of results obtained under headphones is that low-frequency ITDs are more potent than high-frequency ITDs, and thus, receive greater weight when information across frequencies is combined (e.g., Buell and Hafter, 1991; Heller and Trahiotis, 1996; Best *et al.*, 2007). Leaving aside which cues may underlie performance in the free field task, this type of explanation may apply to the current results as well. That is, the baseline MAAs were lower for the low-frequency stimuli (average of 1.5°) than for the high-frequency stimuli (average of 2.1°). This difference was statistically significant according to a paired t-test [$t(5) = 3.02$; $p = 0.030$]. To the extent these thresholds reflect res-

olution “potency” in different frequency regions, they would suggest that interference would be asymmetric in the observed direction.

IV. SUMMARY AND CONCLUSIONS

The MAA was measured for a high-frequency narrow band of noise centered at 4000 Hz (target) in the absence and in the presence of a low-frequency band of noise centered at 500 Hz (interferer). The two signals were presented at the same level, as measured with a microphone at the position of the subject’s head. When the interferer was pulsed on and off with the target and when it was presented from 0° azimuth, there was considerable interference: the average MAA was 13.4° , compared to 2.1° in the absence of the interferer. However, if the interferer was presented continuously, or if it was composed of two stimuli presented from the sides ($\pm 90^\circ$), there was very little interference. These results are consistent with the notion that interference from a remote low-frequency interferer is strongly influenced by the extent to which the target and interferer are fused into a single perceptual object. If cues are provided that promote perceptual segregation (such as temporal onset differences or spatial location differences), the interference is considerably reduced. It was also shown that the interference effect is asymmetric: no interference was observed when the target was a low-frequency noise and when the interferer was a high-frequency noise.

The data and interpretations reported here are generally consistent with those reported in headphone studies (e.g., Bernstein and Trahiotis, 1995; Heller and Trahiotis, 1995b; Buell and Hafter, 1991; Best *et al.*, 2007). However, in contrast to the present results, the headphone studies have not consistently reported a “release from interference” based on spatial separation of the target and interferer. Further study will be required to determine the exact role of spatial separation in free field and headphone interference.

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¹There is some evidence suggesting that the perceived number of objects may not be related so simply to the presence or absence of interference. Woods and Colburn (1992) and Bernstein and Trahiotis (1993) both showed that interference can persist in some cases in which a forward fringe (up to 320 ms) was applied to the low-frequency interfering stimulus. The fringe was sufficient to enable subjects to perceive two objects; yet interference was still measurably greater than when the interferer was continuous. In both of these studies the target was a low-frequency tone. It is not known whether a similar effect would be observed with the typical interference paradigm involving high-frequency targets.

²Of the six hearing-impaired subjects who participated in their study, two had great difficulty in localizing the 4000-Hz stimulus in the presence of the 500-Hz interferer, thus exhibiting interference (Smith-Olinde *et al.*, 1998). The authors attributed this poor performance to a level effect (the subjects had high-frequency sloping hearing losses) and to their consequent inability to ignore the low-frequency interferer.

³Specifically, the virtual image for a given desired angle was produced by activating a pair of loudspeakers on either side of the desired angle, using the law of sines (Pulkki and Karjalainen, 2001, Eq. 2). The angular separation between the two active loudspeakers was always 11.25° (alternate speakers from our array were employed for the panning). Since the panning operation can result in inappropriate ILDs and ITDs for virtual sources in some cases, as described by Pulkki and Karjalainen, we carried out a series of computations based on KEMAR's head-related transfer functions (HRTFs) to compare the interaural differences obtained with real and virtual stimuli, using a 10° separation between the real sources producing the virtual stimuli. Our computations revealed that the ILDs and ITDs behaved normally and monotonically over the range -30° to +30° (measured in 1° steps) for both the low- and high-frequency virtual stimuli, and in cases in which a direct comparison could be made between real and virtual sources, ILD and ITD differences were negligible. Thus, we conclude that the virtual sources do indeed possess proper and appropriate interaural differences over the azimuth range employed in our experiment.

⁴Due to the way the computer program interacted with the hardware, the filter skirts were slightly different, depending on whether each stimulus served as a target or an interferer. When the target was the low-frequency stimulus (centered at 500 Hz), its skirts were 59 dB/octave on both upper and lower sides (they were 48 dB/octave when the low-frequency stimulus served as interferer). When the target was the high-frequency stimulus (centered at 4000 Hz), the skirts were 65 dB/octave and -78 dB/octave on the low- and high-frequency sides, respectively (they were 51 dB/octave and -64 dB/octave when the high-frequency stimulus served as an interferer).

⁵Although the sound pressure levels of the low- and high-frequency stimuli were set to be equal when measured with a microphone at the position of the subject's head, the stimuli arriving to the subject's eardrums would depend on his or her HRTF. Published values of KEMAR's HRTFs indicate that the low-frequency band of noise presented from 0° azimuth would be approximately 14 dB lower in each ear than the high-frequency band (Gardner and Martin, 1995).

⁶Considering the high degree of individual variability, a calculation may be made including only the data from the four subjects who had relatively stable and consistent threshold runs in the PI 0° condition (i.e., those with the lowest thresholds; see Sec. III A 4). This computation of MAA thresholds would result in a three-fold increase (2.1° vs. 6.8°).

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