Binaural interference and auditory grouping

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The phenomenon of binaural interference, where binaural judgments of a high-frequency target stimulus are disrupted by the presence of a simultaneous low-frequency interferer, can largely be explained using principles of auditory grouping and segregation. Evidence for this relationship comes from a number of previous studies showing that the manipulation of *simultaneous* grouping cues such as harmonicity and onset synchrony can influence the strength of the phenomenon. In this study, it is shown that *sequential* grouping cues can also influence whether binaural interference occurs. Subjects indicated the lateral position of a high-frequency sinusoidally amplitude-modulated (SAM) tone containing an interaural time difference. Perceived lateral positions were reduced by the presence of a simultaneous diotic low-frequency SAM tone, but were largely restored when the interferer was "captured" in a stream of identical tones. A control condition confirmed that the effect was not due to peripheral adaptation. The data lend further support to the idea that binaural interference is affected by processes related to the perceptual organization of auditory information. Modifications to existing grouping-based models are proposed that may help account for binaural interference effects more successfully.
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I. INTRODUCTION

Several investigations over the past 30 years have revealed that sensitivity to binaural parameters may be degraded by the presence of simultaneous energy in remote spectral regions. So-called "binaural interference" has been demonstrated for tasks involving discrimination of interaural parameters as well as lateralization on the basis of these cues (McFadden and Pasanen, 1976; Zurek, 1985; Dye, 1990; Trahiotis and Bernstein, 1990; Buell and Hafter, 1991; Woods and Colburn, 1992; Stellmack and Dye, 1993; Buell and Trahiotis, 1994; Bernstein and Trahiotis, 1995; Heller and Trahiotis, 1995, 1996; Hill and Darwin, 1996). The phenomenon is intriguing because it is difficult to reconcile with evidence that simultaneous sounds can be localized quite accurately (Good and Gilkey, 1996; Good *et al.*, 1997; Lorenzi *et al.*, 1999; Best *et al.*, 2005), and with the intuition that listeners have a relatively robust spatial percept of their auditory surroundings.

It is generally agreed that binaural interference results from an obligatory combination of binaural information from spectrally remote components. While some researchers have discussed their data explicitly in terms of auditory object formation (Woods and Colburn, 1992), others do not explain binaural interference in this way. Here we review the binaural interference literature, and show that the bulk of the data is consistent with the idea that binaural interference is a by-product of grouping processes that combine information likely to come from the same auditory object.

A. The basic phenomenon

Binaural interference was first described by McFadden and Pasanen (1976), who observed that just-noticeable differences in interaural time difference (ITD) for a high-frequency narrowband noise were elevated by the presence of a simultaneous low-frequency noise presented diotically. Reduced sensitivity to target ITD was also seen if the target was narrowband and flanked by broadband diotic noise (Zurek, 1985; Trahiotis and Bernstein, 1990), or if the target was a high-frequency sinusoidally amplitude-modulated (SAM) tone in the presence of a low-frequency SAM tone (Heller and Trahiotis, 1995). Furthermore, when presented with a low-frequency tone complex, listeners showed reduced sensitivity to the ITD in one component when one or more components were diotic (Dye, 1990; Woods and Colburn, 1992; Stellmack and Dye, 1993). Binaural interference has also been demonstrated in the detection of interaural level differences (ILDs; Bernstein and Trahiotis, 1995). In general, the data are consistent with the idea that judgments of perceived location underlie the effect. When binaural information is combined across frequencies, the resultant perceived location is only weakly influenced by the target ITD and ILD, and listeners have reduced sensitivity to changes in these parameters.

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B. The influence of simultaneous grouping cues

Several studies have noted that binaural interference only occurs in certain circumstances. A careful review of the literature reveals that binaural interference is most likely to occur when grouping cues support perceiving the target and interferer energy as one object. In particular, many examples show that there is less binaural interference when *simultaneous grouping* cues such as synchronous onsets or harmonicity do not drive the target and masker to be perceptually integrated.

Several studies increased the duration of the interferer such that the target turned on and off during the ongoing interferer rather than being gated on and off simultaneously with it (Trahiotis and Bernstein, 1990; Heller and Trahiotis, 1995). These studies showed that asynchronous gating almost completely eliminated the interference. However, smaller onset asynchronies have produced mixed results. Woods and Colburn (1992) measured ITD discrimination thresholds for a 600-Hz tone target in the presence of two interferer bands (400 and 800 Hz), and found that two out of four of their subjects benefited from an onset asynchrony of 250 ms, but two did not. Using a similar stimulus paradigm but with shorter asynchronies (ranging from 25 to 200 ms), Stellmack and Dye (1993) reported no release from binaural interference due to onset asynchrony. Interestingly, in both of these studies, subjects reported that the pitch of the target component was more salient when there was an onset asynchrony between the target and interferers, suggesting that the asynchrony made it easier to "hear out" the target from the interferer. Thus, subjects segregated the target from the interferers, but did not necessarily perceive it at a different intracranial position. In contrast, Hill and Darwin (1996) showed that listeners could independently lateralize the center component of a tonal complex if the component was delayed by only 80 ms relative to the other components. In their lateralization task, the complex was located on one side of the head, but target localization cues were consistent with a source on the opposite side of the head. It may be that at short onset asynchronies, a larger difference in ITD between the target and the interferers is required to ensure the components are heard at unique locations. The ITD discrimination task used by Woods and Colburn (1992) and Stellmack and Dye (1993) asked listeners to discriminate a small change in target ITD from a reference ITD of zero, in the presence of a diotic interferer. Given the similarity between the target and interferer spatial cues, relatively long onset asynchronies may be required for the target to be localized to a position that is perceptually distinct from that of the interferer (as in the continuous interferer conditions of Trahiotis and Bernstein, 1990, and Heller and Trahiotis, 1995).

Buell and Hafter (1991) assessed the influence of harmonicity on how binaural information is combined across frequency. They presented two low-frequency tones simultaneously, and found that interference only occurred when the tones were harmonically related. When the tones were not harmonically related, listeners were able to ignore the interferer and discriminate the target ITD as accurately as in the target-alone condition. The authors suggested that tones bearing a simple harmonic relation are functionally grouped and their binaural information combined to form the perceived location of the composite object. This conclusion was confirmed by Hill and Darwin (1996), who reported that the perceived lateral position of a target tone is affected when it is played simultaneously with a harmonically related tonal complex, but not in the presence of an inharmonic complex. However, a study by Stellmack and Dye (1993) produced contrasting results, where significant interference was observed even when the target and interferer tones were inharmonic. As the tones used by Stellmack and Dye were more closely spaced in frequency, Hill and Darwin (1996) suggested that some monaural interference may have occurred. In addition, however, Hill and Darwin used competing locations on opposite sides of the head, whereas Stellmack and Dye used competing locations near the midline. As was noted for segregation based on onset asynchrony, the binaural system may require stronger evidence from harmonic segregation rules when binaural conflicts are small across frequency.

C. The influence of sequential grouping cues

If binaural interference is related to how listeners perceptually organize a sound mixture into objects, then sequential grouping rules (as well as simultaneous grouping rules) should influence the strength of the interference observed. The experiment presented in this paper was conducted to examine whether a target and interferer pair (with common onsets and offsets) could be "ungrouped" by capturing the interferer in a repeating auditory stream. This manipulation is similar in its philosophy to the "continuous interferer" stimulus in previous studies (Trahiotis and Bernstein, 1990; Heller and Trahiotis, 1995), but it preserves the local structure of the target/interferer pair (including common onsets and offsets). Thus, any effect of the sequential stream on binaural interference implicates grouping and streaming mechanisms that operate over relatively long time scales. Sequential capture has been shown previously to successfully promote the segregation of complex sounds. For example, it reduced the contribution of a component to the pitch and timbre of a harmonic complex (Darwin *et al.*, 1989; 1995) and it reduced modulation detection interference (Oxenham and Dau, 2001). It should be noted that observing a reduction in interference when the interferer is captured into a separate stream does not necessarily demonstrate that interference is caused by grouping of the target and interferer. However, it emphasizes that binaural interference is influenced by the perceptual organization of the components involved.

D. Measuring perceived location

Most studies of binaural interference measured it using an ITD discrimination task in the presence of a diotic interferer. The results are largely consistent with a model in which binaural information is combined in an obligatory fashion across frequencies in the absence of strong cues to allow the target to be heard as an independent object. An interaurally uncorrelated interferer (i.e., containing no con-

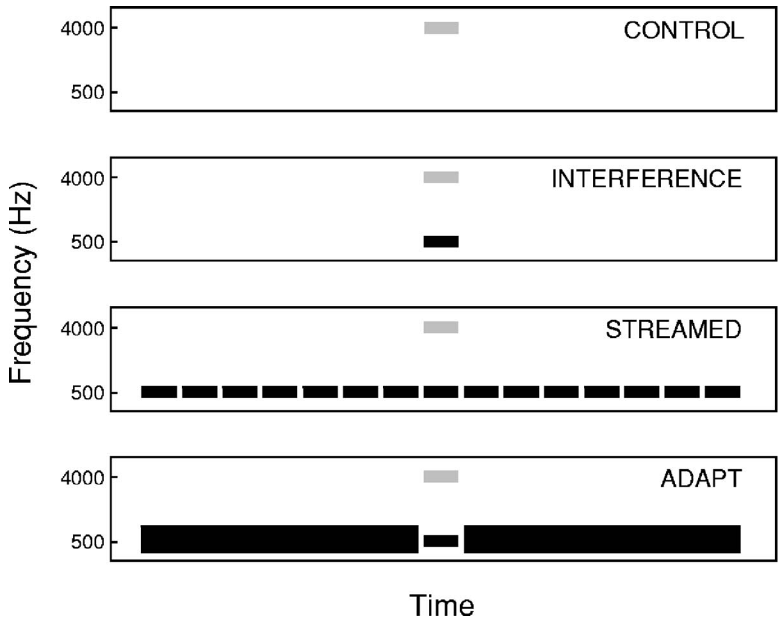

FIG. 1. Schematic illustration of the experimental stimuli. In the control condition, the high-frequency target was presented in isolation. In the interference condition, a simultaneous low-frequency interferer was presented. In the streamed condition, the interferer was flanked on either side by seven identical captor tones. In the adapt condition, the flanker tones were replaced by a sustained narrowband noise that spanned the frequency range of the flanker tones but was different in quality (and hence unlikely to be grouped with the interferer).

sistent binaural information) was shown to cause far less interference than a diotic interferer (Trahiotis and Bernstein, 1990). This is to be expected if spatial information is combined across frequencies. The target binaural information will dominate when the interferer has no strong spatial information, which will allow small changes in target ITD to cause relatively large changes in the perceived location of the composite object. However, a stronger test is to directly measure the perceived lateral position of a target in cases where there is an interferer present and examine whether the perceived location is predicted from the combination of spatial cues present in the target and interferer.

Only two of the studies discussed above directly measured perceived location under binaural interference conditions (Heller and Trahiotis, 1996; Hill and Darwin, 1996). These data confirm that the perceived laterality of the target is influenced by the lateral position of the interferer when binaural interference occurs. It appears that a synchronous interferer “attracts” the perceived target location either fully (in the case of a pure-tone target embedded in a seven-component tonal complex; Hill and Darwin, 1996) or partially (in the case of a high-frequency target and a single low-frequency interferer; Heller and Trahiotis, 1996). We know of no investigations that have examined the effect of lateralized interferers on the perceived lateral position of a target near the midline (although lateralized interferers do reduce ITD sensitivity in targets similar to diotic interferers; Buell and Hafter, 1991). In the experiment described in this paper, perceived target laterality was measured directly using a paradigm similar to that of Heller and Trahiotis (1996).

II. METHODS

A. Subjects

Eight listeners participated in the experiment (one female, seven male). All had normal audiograms and four had previous experience in psychophysical listening (S1–S4; S1 was the first author). All subjects gave informed consent to participate, required by the Boston University Charles River Campus Institutional Review Board.

B. Stimuli

The target stimulus was a high-frequency SAM tone (4-kHz carrier, 250-Hz modulation rate, 250-ms duration, 10-ms raised-cosine ramps at onset/offset). It was presented in four different conditions (see Fig. 1). In the “control” condition the target was presented with no interferer. In the “interference” condition, the target was presented with a single simultaneous interferer. The interferer was a low-frequency SAM tone (500-Hz carrier, 250-Hz modulation rate, 250-ms duration, 10-ms raised-cosine ramps at onset/offset). The “streamed” condition was identical to the interference condition, except the interferer was flanked temporally by identical tones (seven preceding and seven following, giving 15 tones in the stream in total). The interferer tones were separated by 50 ms of silence. As a control for any adaptation that might be caused by the flanking tones, an “adaptation” condition was included. In this condition, a narrowband noise was presented in place of the seven leading (and trailing) tones. The noise was bandpass filtered between 100 and 1000 Hz, and was scaled to be 6 dB higher in level than the stream of tones in a one-third-octave band centered at 500 Hz. It was assumed that the noise would cause at least as much adaptation as the stream of tones,[1] but would not group with the interferer tone.

The target was presented with an ITD that varied from trial to trial, taking one of seven values (0 μs, ±200 μs, ±400 μs, or ±600 μs). ITDs were created by delaying the entire waveform (both envelope and fine structure) in one ear. The interferer, when present, was presented diotically (0 μs ITD).

C. Procedures

Subjects were seated in a sound-treated booth in front of a PC terminal. Digital stimuli were generated on the PC, sent to Tucker-Davis Technologies hardware for D/A conversion and attenuation, and presented over insert earphones (Etymotic Research ER-2).

The four different conditions were tested in separate blocks of trials. Each block consisted of five trials at each of the seven ITD values, for a total of 35 trials. On each trial, subjects were presented with a random stimulus, and their task was to indicate the perceived location of the target using an ILD pointer. The ILD pointer was a high-frequency SAM tone identical to the target, whose lateral position was adjusted by increasing the level of the signal going to one ear. The pointer was presented (with an initial ILD of 0 dB) immediately after the initial presentation of the stimulus. Subjects used a graphical user interface displayed on the PC monitor to move the pointer to align it with the perceived lateral position of the target in the test stimulus. "Left" or "right" buttons increased or decreased the pointer tone ILD by 1 dB. A "replay" button allowed replay of the test stimulus followed by the pointer tone. Subjects moved the pointer tone and replayed the test stimulus until they were satisfied that the lateral positions matched.

Before commencing the test blocks, subjects were given detailed verbal instructions about the task. They were told to listen for the lateral position of the high-pitched target and were given a short practice test to familiarize them with the matching task. The practice test consisted of 14 trials of the control stimulus (two at each of the seven target positions, presented in a random order). Subjects were also given a description of the different conditions, and were played examples of each. They were instructed to ignore the low-pitched sounds when they were present. They were told that if they could not distinguish the simultaneous high- and low-pitched sounds then they should simply locate the sound they heard.

Two blocks of each of the four conditions were completed by each subject in a random order, with the constraint that one block of each condition was completed before any condition was revisited.

III. RESULTS

For each subject in each block of trials, mean position responses over the five repetitions were calculated for the seven target locations. In some cases, subjects showed a small lateral bias in their mean response to stimuli presented diotically (0-μs ITD), which may have been due to earphone placement or small asymmetries in the ears. To correct for this bias, the mean perceived ILD for diotic stimuli was subtracted from all responses in that block (see Bernstein and Trahiotis, 1985). Responses to target positions left of midline were then mirror-flipped and combined with responses to target positions right of midline. Finally, zero-adjusted and mirror-flipped data from the two blocks in each condition were pooled for each subject.

Figure 2 shows results for the individual subjects in the control, interference, and streamed conditions.[2] Lateral estimates are on the whole greatest in the control condition (solid lines) and tended to be reduced in the interference condition (dashed lines). These results are consistent with Heller and Trahiotis (1996), and consistent with the idea that binaural information is combined across the two frequency regions to give rise to a composite perceived location. However, there are substantial individual differences in the amount of interference that occurred. In particular, subjects S7 and S8 showed essentially no interference (and, interestingly, showed the smallest extents of laterality in the control condition). For all listeners who did show interference, the presence of the leading and trailing tones in the streamed condition reduced this interference (dotted lines). For some subjects (e.g., S5), lateral percepts were restored almost completely, and responses were close to the control condition. For other subjects (e.g., S2), the interference was reduced but not fully eliminated. The mean data, pooled across subjects, are shown in Fig. 3 and summarize these effects. Also shown in Fig. 3 are the mean data from the adapt condition (dash-dot lines). In this condition, responses were almost identical to the interference condition. A two-way repeated measures ANOVA was conducted on the mean data with factors of condition (control, interference, streamed, and adapt) and target location (all except 0 μs). The main effect of condition was significant [$F(3,21)=19.78$, $p<0.001$], as was the main effect of location [$F(2,14)=220.56$, $p<0.001$] and the two-

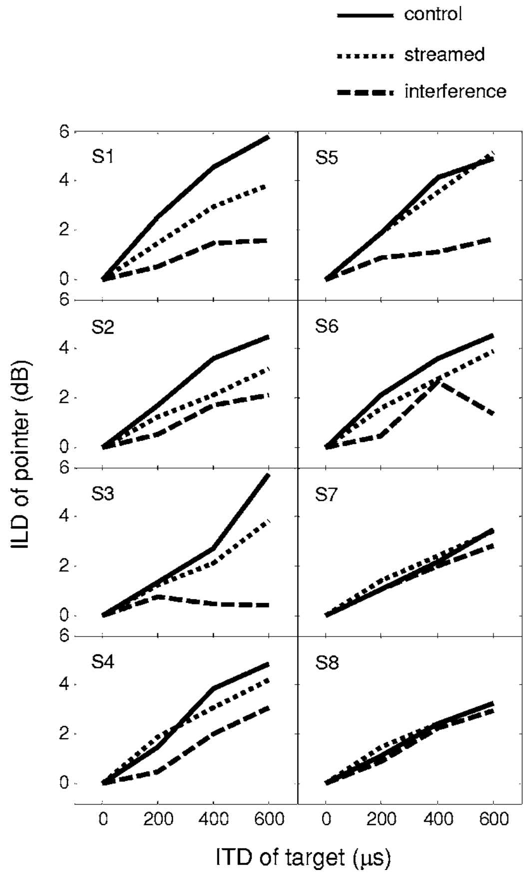

FIG. 2. Lateralization results for the eight individual subjects. Perceived lateral position of the target (indicated by matching to an ILD pointer) is shown as a function of target ITD. Different lines indicate mean responses for the control condition (solid lines), the interference condition (dashed lines), and the streamed condition (dotted lines).

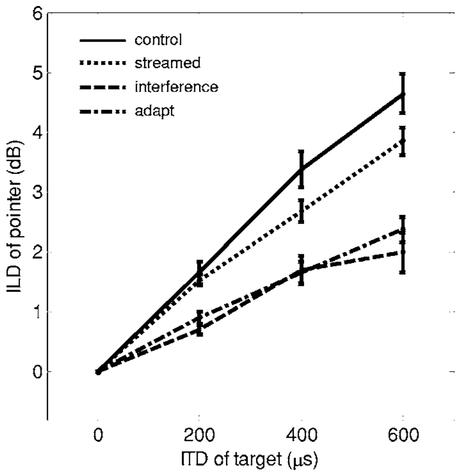

FIG. 3. Mean lateralization results pooled across subjects. Perceived lateral position of the target (indicated by matching to an ILD pointer) is shown as a function of target ITD. Different lines indicate mean responses for the control condition (solid lines), the interference condition (dashed lines), the streamed condition (dotted lines), and the adapt condition (dash-dot lines). Error bars represent standard errors of the across-subject mean.

way interaction $[F(6,42)=7.42,\ p<0.001]$. As the effect of condition was of primary interest, pairwise comparisons were done across conditions. These revealed that the control condition was significantly different from all other conditions ($p<0.05$). The interference condition was significantly different from both the control and streamed conditions ($p<0.01$), but was not different from the adapt condition ($p=0.16$), supporting the idea that binaural interference was abated by the sequential stream but not by the adapting noise. Further confirming this point, mean responses in the streamed and adapt conditions were significantly different ($p<0.01$).

IV. DISCUSSION

The key condition of interest in this experiment was the streamed condition. The fact that responses in this condition are more similar to responses in the control condition than the interference condition indicates that when the interferer was presented in the context of a sequential stream, the ability to assess the ITD of the target improved compared to when there were no flanking tones. The fact that a similar reduction in interference did not occur for the narrowband noise flankers in the adapt condition indicates that the reduction cannot be due merely to the presence of leading and trailing energy in the frequency region of the interferer. In other words, the effect of the sequential stream does not appear to be due to peripheral adaptation that reduces the neural representation of the interferer. Rather, the most parsimonious explanation is that the sequential stream (including the interferer) formed a perceptual object, allowing the target to be perceived and processed as a distinct object. Consistent with this idea, subjects who showed release from interference reported that they could hear out the target far more easily in the streamed condition than in the interference and adapt conditions.

These results support previous evidence suggesting that auditory grouping cues play a strong role in determining how spatial information is combined across frequency. It appears that binaural interference is the result of obligatory grouping that occurs when there are no cues indicating the presence of two distinct sound sources (other than the spatial cues themselves). This is consistent with evidence that spatial information in isolation is a relatively weak cue for promoting the segregation of simultaneous sounds (Culling and Summerfield, 1995; Darwin and Hukin, 1999). However, introducing strong segregation cues (asynchronous onsets, inharmonicity, a sequential stream) reduces the obligatory grouping across frequency and improves the ability to independently access binaural information from sounds in different frequency regions.

Surprisingly, there has been no attempt to fully develop a scene-analysis-based explanation of binaural interference phenomena, perhaps because of what at first glance appear to be puzzling exceptions to such an account. First, it is clear that segregation of sounds does not always give perfect release from binaural interference; extraneous energy can still influence binaural processing in a clearly segregated sound. Indeed, for the majority of the subjects in the current study, interference was reduced but not eliminated in the streamed condition. One possible reason for this residual influence is that listeners do not perform optimally in complex tasks of this nature. Good evidence for this idea comes from the fact that binaural interference increases when the target frequency region is uncertain (Buell and Trahiotis, 1994). Furthermore, in many cases where listeners exhibit nonoptimal strategies for coping with "central" forms of interference, there also tend to be large individual differences. Consistent with this, a striking feature of binaural interference studies is the large amount of variation across individuals (Woods and Colburn, 1992; Heller and Trahiotis, 1995; present study). It is likely that listeners differ in their ability to isolate and attend selectively to the target interaural delays even when there are clear cues supporting segregation of target and interferer. Individual differences in this ability to listen "analytically" have been observed for binaural discrimination (Dye *et al.*, 1996; Stellmack and Lutfi, 1996). Furthermore, Dye and colleagues (2005) showed that these individual differences predict individual performance in a monaural discrimination task. The ability to weight different frequency regions selectively is also highly relevant in many studies of informational masking (Durlach *et al.*, 2003; Alexander and Lutfi, 2004; Richards and Neff, 2004), and in such studies, as in binaural interference studies, large individual differences are observed. In short, it is likely that different perceptual strategies influence the amount of interference observed in binaural interference studies. Finally, there are suggestions in the literature that listener exposure can affect susceptibility to interference (Woods and Colburn, 1992; Stellmack and Dye, 1993; Hill and Darwin, 1996), suggesting that experience with a particular task can lead to a more refined ability to hear out a target from a complex mixture.

A second puzzle concerns the fact that low-frequency sounds interfere much more strongly with high-frequency targets than vice versa (McFadden and Pasanen, 1976; Zurek, 1985; Trahiotis and Bernstein, 1990; Heller and Trahiotis, 1995). However, it is well known that low-frequency

ITDs are more potent than high-frequency ITDs (Henning, 1980; Bernstein and Trahiotis, 1982; Shinn-Cunningham *et al.*, 1995), and thus might be expected to be weighted more heavily when information is grouped across frequency. Indeed, "transposed tones" (which provide high-frequency channels with ITD information that is as potent as low-frequency ITDs) appear to be immune to binaural interference from a low-frequency noise interferer (Bernstein and Trahiotis, 2004, 2005). It is somewhat surprising that no interference occurs for these pairs, as their simultaneous onsets and offsets would predict some obligatory grouping. It is worth noting, however, that transposed tones have unusual spectral and temporal characteristics, including the exaggerated temporal envelope fluctuations that provide the basis for the robust ITD cues. It may be that the envelope of a transposed tone differs so much from that of the low-frequency noise that they are not perceptually grouped into the same object (McFadden, 1987; Hall *et al.*, 2006). It would be useful to contrast monaural and binaural interference for these stimuli (e.g., see Dye *et al.*, 2005) to determine how much grouping does in fact occur.

A final concern that has been raised in discussions trying to relate binaural interference phenomena directly to grouping processes is that models based on grouping have failed to explain the data completely. Models based on an obligatory weighted combination of binaural information across frequency have done quite well at predicting ITD thresholds under conditions of binaural interference (Buell and Hafter, 1991; Heller and Trahiotis, 1996). However, predicting "release" from binaural interference when segregation cues are introduced has proven more challenging. Woods and Colburn (1992) extended the Buell and Hafter model to include a stage where frequency channels are parsed according to the object with which they are associated. When applied to three-tone complexes, the model generally overpredicted performance (i.e., predicted less interference) in the case where the central target component was segregated on the basis of onset asynchrony. Importantly, their model assumed perfect parsing with no residual interference between frequency channels when computing perceived locations. The authors acknowledged that a "central noise source," perhaps related to imperfect segregation of the tone or poor focus of attention, might be required. Indeed, in order to account for the aforementioned individual differences in results, such a stage is not only necessary, but must incorporate individualized nonoptimal weightings in the manner of Dye and colleagues (2005). An important observation made by Woods and Colburn was that perceptual segregation ("hearing out" the target tone) occurred reliably with asynchronous onsets even in cases where binaural interference persisted. Their conclusion was that it is necessary but not sufficient to hear out the target as a separate object for release from binaural interference to occur (a conclusion supported by the streamed condition of the current study). A complete grouping-based model of binaural perception may involve two decision stages; one stage determining the number of objects present, and another where the objects are localized (for a related idea see Litovsky and Shinn-Cunningham, 2001). In order to hear the different objects and distinct locations, the magnitude of the spatial disparity required may be inversely related to the weight of evidence supporting the presence of multiple objects.

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[1]In a recent study, Roberts and Holmes (2006) demonstrated that the addition of simultaneous frequency components to a pure tone reduces the effective level of the tone (presumably via broadband inhibition). In light of this, it is possible that increasing the bandwidth of the leading portion resulted in a less effective stimulus at 500 Hz. While the fact that we increased the level of the noise by 6 dB may have counteracted this effect, we cannot know with full certainty that the effective level of the noise at 500 Hz (and hence its ability to adapt) was as great as the sequential tones.

[2]It is worth pointing out that the pointer estimates fall into a relatively compressed range overall (±6-dB ILD). These values are smaller than those reported by Heller and Trahiotis (1996), who also used an ILD pointer to indicate the location of similar target stimuli. We believe the difference lies in the characteristics of the pointer stimulus: Heller and Trahiotis used a narrowband noise centered at 500 Hz, while in the current study we used a 4000-Hz SAM tone. Our experience with the high-frequency pointer is that it saturates relatively quickly, such that further increases in ILD do not give rise to substantial increases in perceived lateral displacement. The small range of pointer ILDs suggests that listeners restricted their responses to most useful region of the dynamic range.

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