

# Lateralization of a perturbed harmonic: Effects of onset asynchrony and mistuning<sup>a)</sup>

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The lateralization paradigm of Trahiotis and Stern [C. Trahiotis and R. M. Stern, *J. Acoust. Soc. Am.* **86**, 1285–1293 (1989)] was extended to investigate the influence of a spectrally flanking complex on the lateral position of a perturbed harmonic. When a complex tone consisting of harmonics 2 through 8 of 100 Hz was presented with an interaural time difference (ITD) of 1.5 ms, the complex was heard on the leading side (experiment 1). However, when the 500-Hz component had a later onset time than the other components (experiments 1 and 2) or was mistuned (experiment 3), it was perceived to be in a different lateral position to the complex. The complex still maintained a residual influence on the lateralization of the pure tone even for the largest asynchrony used (experiment 4). Experiment 5 confirmed that the lateralization of the tonal complex was consistent with the aggregation of binaural information across frequency. The results suggest that across-frequency integration of interaural-timing information is influenced by onset-asynchrony and harmonicity. © 1996 Acoustical Society of America.

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## INTRODUCTION

Evidence from a number of studies suggests that the perceived lateral position of complex stimuli is determined by pooling binaural information across frequency. This evidence comes both from measurements of listener sensitivity to changes in the interaural parameters of target bands of energy (e.g., McFadden and Pasanen, 1976; Dye, 1990; Buell and Hafter, 1991), and from measurements of the variation of lateral position with stimulus bandwidth (e.g., Trahiotis and Stern, 1989).

In the first report of an effect of extraneous energy on interaural time difference (ITD) discrimination, McFadden and Pasanen (1976) observed that the threshold ITD for a band of noise 230 Hz wide and centered at 4 kHz was increased by approximately a factor of 2 following the introduction of a second, synchronously gated diotic band of noise centered at 500 Hz. This decrease in sensitivity to ITDs in high-frequency bands of noise in the presence of extraneous energy has been reaffirmed in subsequent studies using spectrally flanking noise as the interferer (Zurek, 1985; Trahiotis and Bernstein, 1990). Of particular relevance was the finding by Trahiotis and Bernstein that much greater interference was observed when the flanking noise was diotic, than when it was uncorrelated between the ears, suggesting that at least some of the interference was due specifically to the across-frequency processing of binaural information.

Significant binaural interference has also been observed between low-frequency tonal stimuli (Dye, 1990; Buell and Hafter, 1991; Woods and Colburn, 1992; Stellmack and Dye, 1993). Dye (1990) found that the threshold for detecting an

ITD in a single component of a three-component complex was significantly greater than that for the same component in isolation, even when the frequency components were well resolved. In another experiment from the same series Dye found that the threshold ITD for a five-tone complex decreased linearly as the number of components to which the ITD was applied increased. These results are consistent with the idea that when listening to multitone stimuli listeners perceive a single image the lateral position of which is determined by aggregating binaural information across the separate components.

Direct evidence that the lateralization of broadband stimuli involves the integration of binaural information across frequency comes from measurements of the lateral position of interaurally delayed bands of noise (Jeffress, 1972; Trahiotis and Stern, 1989). Trahiotis and Stern measured the lateralization of bands of noise centered on 500 Hz and interaurally delayed by 1.5 ms. When the bandwidth of the noise was 50 Hz, the sound was heard toward the ear receiving the lagging signal because of phase ambiguity and the auditory system's preference for short delays. However, when the width of the noise was increased to 400 Hz, the lateral position of the noise shifted toward the ear receiving the leading signal. The reason advocated by Stern *et al.* (1988) is that the only peak in the cross-correlation function that is consistent across frequency is at 1.5 ms (corresponding to the actual delay). The other peaks will vary in latency with frequency channel. Consistency of the 1.5-ms peak across frequency then overrides the greater weighting given to the shorter-latency cross-correlation peaks, whose delay varies across frequency channels.

While the integration of binaural information across frequency may lead to more reliable estimates of lateral position by reducing phase ambiguities, the ability of the auditory system to lateralize stimuli in a multisource environment may be impaired if binaural information is

<sup>a)</sup>The experiments described here formed part of the first author's D. Phil. dissertation (Hill, 1994). Some of the results described here were previously reported in Hill and Darwin (1993). Dr. Hill is now at the Department of Psychology, University of York, York YO1 5DD, UK (E-mail: nih1@york.ac.uk).

combined indiscriminately across different auditory objects. One solution to this problem would be to combine information selectively across frequency such that only those frequency components or regions that show evidence of originating from a common source actually contribute to that source's lateralization. Two of the most important cues that the auditory system might use for identifying those components that belong to a common source are common onset time (e.g., Dannenbring and Bregman, 1978; Darwin, 1984; Roberts and Moore, 1991; Darwin and Ciocca, 1992) and, for periodic stimuli, the existence of a common fundamental (e.g., Darwin, 1981; Moore *et al.*, 1985; Hartmann *et al.*, 1990).

The extent to which segregational cues can influence the amount of binaural interference (and arguably, therefore, the extent to which information is combined across frequency) has been investigated in a number of studies. For example, Buell and Hafter (1991) measured the threshold ITD for two-tone complexes in which one tone was presented with an ITD while the other was diotic. When the tone pair was inharmonic, threshold ITD was comparable with that for the interaurally delayed tone in isolation. However, when the pair of tones was harmonically related, the threshold ITD increased significantly. This result is consistent with the idea that harmonicity leads to the target and interferer being treated as a single object with both components contributing to that object's lateralization. This finding of an effect of harmonicity on the amount of binaural interference contrasts with the results of a detailed series of experiments by Stellmack and Dye (1993) in which significant interference was observed even when the target and interferer tones were inharmonic.

With regards onset asynchrony, it appears that merely gating the interferer on ahead of the target results in little if any reduction in binaural interference (Woods and Colburn, 1992; Stellmack and Dye, 1993; Bernstein and Trahiotis, 1993). However, there is some evidence that interference is reduced significantly if the masker is presented continuously (Trahiotis and Bernstein, 1990; Bernstein, 1991; Bernstein and Trahiotis, 1993, 1995). For example, Bernstein and Trahiotis (1993) using a masking level difference paradigm found that while gating the interferer on 320 ms ahead of the target had no significant effect on the amount of interference, interference was reduced significantly when the interferer was continuous.

The aim of the present series of experiments is to investigate further the extent to which grouping cues can influence across-frequency integration of interaural-timing information. The experiments employed a tonal analogue of the noise stimulus described by Trahiotis and Stern (1989) namely, a seven-component complex centered on 500 Hz comprising the second through eighth harmonics of a 100-Hz fundamental. When the central 500-Hz component of this complex is presented alone with an interaural delay of 1.5 ms, it is perceived on the lagging side of the head due to the inherent phase ambiguity coupled with the auditory system's bias for short delays. However, when the entire complex is presented with an ITD of 1.5 ms, informal listening indicated that a single image is perceived lateralized on the leading

side of the head. This result is analogous to that observed by Trahiotis and Stern (1989) in connection with noise stimuli and suggests that the lateralization of tonal complexes is also based on the integration of binaural information across frequency.

The present experiments investigated the role of grouping on binaural processing by measuring the perceived lateralization of the 500-Hz component of the complex when it had been perceptually segregated as a result of changes to its onset time or harmonicity. If binaural information is integrated across all components that are present at a given time regardless of the object to which they belong, then both the complex and the segregated component should be perceived in similar positions. However, if the auditory system only combines information across components for which there is evidence of a common source, then the complex and the segregated harmonic should be perceived on opposing sides of the head.

## I. GENERAL METHOD

### A. Equipment

Signal generation and experimental control were performed by a Macintosh IICI equipped with a Digidesign Audiomedia board. Stimuli were synthesized in real time at a sampling rate of 22.05 kHz using the board's 56001 processor (Russell and Darwin, 1991; Russell, 1992) and were converted to analogue signals using the board's 16-bit DACs. The signal was then low-pass filtered at 10 kHz for antialiasing and suitably attenuated (Tucker-Davies Technologies). The attenuated output was fed into a double-walled IAC booth where it was presented binaurally to the listener over matched Sennheiser HD414 headphones. Through the booth's window, the listener could view a monitor connected to the Macintosh computer.

### B. Procedure

Lateralization estimates were obtained using a matching procedure similar to that described by Bernstein and Trahiotis (1985). Each trial began with three presentations of a target signal followed by two presentations of a pointer stimulus. The initial interaural intensity difference (IID) of the pointer was assigned randomly from the range  $-30$  dB (full left) to  $+30$  dB (full right). Following presentation of the target-pointer sequence, a cross-hair icon was displayed in the center of the computer screen. The listener could adjust the screen position of the cross-hair icon using a mouse controller. Depressing the mouse button replayed the target-pointer sequence with the pointer IID adjusted by an amount proportional to the horizontal displacement of the cross-hair icon from the center.<sup>1</sup> Attempts to set the IID of the pointer to a value outside the range  $\pm 30$  dB resulted in the presentation of a brief warning tone, following which the pointer would be reset in a random position. By repeating this procedure listeners were able to adjust the perceived lateral position of the pointer to match that of the target sound. When satisfied with the match, depressing an appropriate pair of keys on a keyboard registered the pointer IID and initiated the next trial.

### C. Listeners

The seven listeners (two male, five female) who participated in these experiments all had normal pure-tone thresholds in both ears. Additionally, none of the listeners reported any history of hearing problems. The ages of the listeners ranged between 18 and 21 years. Four listeners (CBC, DM, SP, and NC) were musically trained, and had participated in a previous series of psychoacoustic experiments within the laboratory. All listeners received a minimum of 5 h matching practice prior to collection of the reported data. RS became unavailable after experiment 1 and was replaced in the subsequent experiments by KH. Listeners were paid at the rate of £3.50 per hour.

## II. EXPERIMENT 1

The objectives of this experiment were first, to extend to interaurally delayed periodic stimuli the observation of Trahiotis and Stern (1989) for noise, and second, to investigate whether the implied across-frequency processing underlying this phenomenon was influenced by the relative onset time of the individual components of the complex. If, as suggested by the results of binaural interference experiments (e.g., Stellmack and Dye, 1993), binaural information is aggregated over all components that are present at a given time irrespective of their relative onsets, then a component having a delayed onset should be perceived in the same lateral position as the rest of the complex. However, if binaural information is only aggregated across frequency components for which there is sufficient evidence of a common source, then an asynchronous component should be lateralized independently of the remainder of the complex.

### A. Procedure

The target stimulus was always a seven-component complex comprising a 500-Hz tone flanked on either side by the three adjacent harmonics of 100 Hz. In the synchronous onset condition, all components were gated on at the same time with a 10-ms attack, were maintained at a steady amplitude for 160 ms and were then gated off with a 230-ms decay giving a total duration of 400 ms. The shape of the attack and decay trajectories were approximately exponential, a choice motivated by the observation by Cohen (1980) that gating complex stimuli on with a fast attack and off with a relatively slow exponential decay enhances their perceived fusion. The components in the asynchronous onset condition were similarly shaped except that the onset of the 500-Hz tone was delayed by 80 ms relative to that of the other components. The duration of the steady-state portion of this component was correspondingly reduced by 80 ms so that all components terminated synchronously. The level of each component was 54 dB SPL.

Five values of target ITD were used: 0,  $\pm 0.5$ , and  $\pm 1.5$  ms, with positive values indicating that the right-ear signal was leading. These were produced by advancing the phase of each frequency component by the appropriate amount under envelopes which were the same in both ears. All components of the lagging signal were gated on in sine phase. The five values of ITD were combined with the two gating conditions

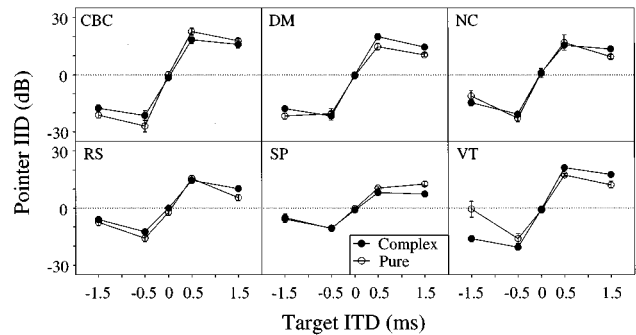


FIG. 1. Mean value of pointer IID ( $\pm 1$  s.e. across four repetitions) as a function of ITD for target stimuli consisting of harmonics 2 through 8 of a 100-Hz fundamental gated synchronously in experiment 1. Open symbols denote matches made using a 500-Hz pure-tone pointer, while solid symbols denote matches made using a complex pointer consisting of harmonics 2–4 and 6–8 of 100 Hz. Positive values of an interaural difference denote a greater intensity or lead time at the right ear.

to give a total of ten different stimulus conditions. Each condition was presented four times in a random order to give a total session length of 40 trials.

At the beginning of each trial listeners were presented with a stimulus sequence which consisted of three repetitions of the target stimulus (each separated by 30 ms), a pause of 70 ms and then two repetitions of the pointer (again separated by a silent interval of 30 ms). Since in the asynchronous onset condition the target would comprise two images, listeners were able to toggle between two pointer stimuli, one corresponding to the pure tone, the other corresponding to the flanking tones. The task of the listeners was to adjust the lateral position of each pointer to match that of the appropriate image in the target stimulus. Each of the pointer stimuli was spectrally identical to its corresponding counterpart in the target stimulus, had a fixed duration of 400 ms and was gated on and off using an identically shaped envelope to that of the target. Each component of the pointer was presented with an equal amplitude corresponding to 52 dB SPL for a 1-kHz tone when the pointer IID was zero. When, as was likely to be the case in the synchronous onset condition, listeners were unable to “hear out” the pure tone, they were instructed to match both the pure tone pointer and the complex pointer to the single fused image. The reported data for each listener were obtained from a single session of approximately 1-h duration.

### B. Results

The mean value of pointer IID for each condition together with the corresponding error bars denoting one standard error of the mean are shown separately for each listener in Figs. 1 and 2. Figure 1 shows matches made in the synchronous onset condition and Fig. 2 matches made in the asynchronous onset condition. Figure 3 shows a comparison of the data for the synchronous and asynchronous conditions averaged over the six listeners.

The data were subjected to a fixed factors analysis of variance with repeated measures, the factors being listener (6), pointer type (2), gating condition (2) and ITD (5). Each cell in the model comprised four data points, these being the

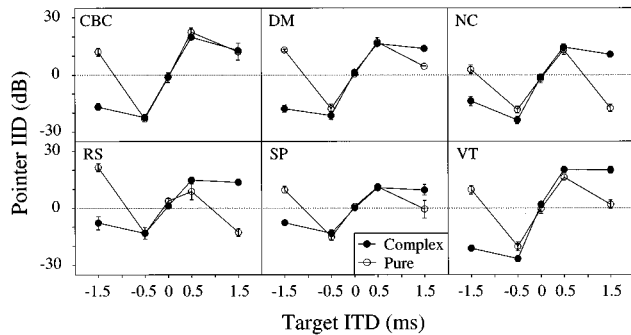


FIG. 2. Mean value of pointer IID ( $\pm 1$  s.e. across four repetitions) as a function of ITD for target stimuli consisting of harmonics 2 through 8 of a 100-Hz fundamental in experiment 1. The onset of the 500-Hz component was delayed by 80 ms relative to that of the flanking components. Open symbols denote matches made using a 500-Hz pure-tone pointer, while solid symbols denote matches made using a complex pointer consisting of harmonics 2–4 and 6–8 of 100 Hz. Positive values of an interaural difference denote a greater intensity or lead time at the right ear.

four matches for each listener in each condition. There were significant main effects of listener ( $F_{5,360}=8.73$ ,  $p<0.0005$ ), interaural delay ( $F_{4,360}=1263.61$ ,  $p<0.0005$ ), gating condition ( $F_{1,360}=4.07$ ,  $p<0.05$ ), and pointer type ( $F_{1,360}=8.55$ ,  $p<0.005$ ). There was also a significant interaction between gating condition and pointer type ( $F_{1,360}=12.29$ ,  $p<0.001$ ) indicating that the relative positions of the complex and pure-tone pointers differed across the two conditions. The matches obtained with the two types of pointer were compared both within and across the two gating conditions by means of planned comparisons. There was no significant difference between the matches made using complex and pure-tone pointers in the synchronous onset condition ( $p>0.6$ ) nor between the matches for the complex pointer across the two gating conditions ( $p>0.2$ ). There were, however, significant differences between the complex and pure-tone matches in the asynchronous condition ( $p<0.0005$ ) and between the matches for the two pure-tone pointers across the two conditions ( $p<0.0005$ ).

The subjective reports of the listeners indicated that in the synchronous onset condition they were generally unable to hear out the 500-Hz target tone. This finding is consistent with the matching data which shows no significant difference between the matches made using the two pointers when the

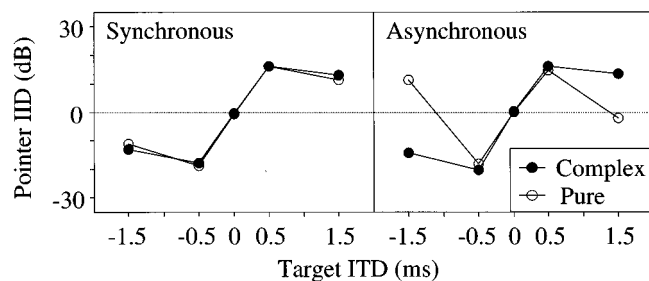


FIG. 3. Average data for experiment 1 pooled across the six listeners. Open symbols denote matches made using a 500-Hz pure-tone pointer, while solid symbols denote matches made using a complex pointer consisting of harmonics 2–4 and 6–8 of 100 Hz. Positive values of an interaural difference denote a greater intensity or lead time at the right ear.

500-Hz tone was gated synchronously. The variability in listener VT's data for the  $-1.5$ -ms condition does, however, suggest that she may have perceived multiple images on at least some trials in this condition. From Fig. 1 it can be seen that for all listeners other than VT, the mean values of IID for both pointer stimuli in the synchronous onset condition are consistent with the fused image being lateralized on the side of the head receiving the leading signal. Generally, the matches made using the complex pointer in the  $\pm 1.5$ -ms conditions are nearer the mid-line than in the  $\pm 0.5$ -ms conditions. Analyzed over listeners, both the difference between the  $-0.5$ - and  $-1.5$ -ms conditions and that between the  $0.5$ - and  $1.5$ -ms conditions were significant (planned comparisons,  $p<0.0005$  and  $p<0.005$ , respectively).

In the conditions where the 500-Hz tone was asynchronous, a very different pattern of results emerged. Now, all listeners reported that the target comprised two images and that they were able to match each pointer to the appropriate image.

The data for the asynchronous onset condition show that when the target was presented with an ITD of  $\pm 0.5$  ms, both the flanking complex and the 500-Hz tone were lateralized in approximately the same position, on the leading side of the head. However, when the target was presented with an ITD of  $\pm 1.5$  ms, the 500-Hz tone was generally lateralized on, or at the very least displaced toward the lagging side of the head. There is some asymmetry between the  $+1.5$ - and  $-1.5$ -ms conditions with five of the six listeners showing a smaller mean displacement of the 500-Hz tone from the complex when the ITD was  $+1.5$  ms.

### C. Discussion

The data confirm that a tonal complex comprising the 2nd through 8th harmonics of 100 Hz is lateralized toward the leading side of the head when presented with an interaural delay of  $\pm 1.5$  ms. This result extends to periodic stimuli the observation of Trahiotis and Stern (1989) for bands of noise and is consistent with the idea that the lateral position of harmonic multitone stimuli is determined from binaural information pooled across the individual components.

For a binaurally presented 500-Hz tone with interaural delays applied solely to the fine structure, an ITD of 1.5 ms is equivalent to an ITD of  $-0.5$  ms. Therefore, the finding that listeners generally perceived the asynchronous 500-Hz component displaced toward the ear receiving the lagging signal when presented with an ITD of  $\pm 1.5$  ms (Fig. 2) suggests that onset asynchrony may facilitate the independent lateralization of concurrent sounds. For most listeners, however, the flanking components still maintained a significant influence on the lateralization of the 500-Hz tone. The degree to which the lateral position of the 500-Hz component was affected by the flanking tones varied significantly across listeners, particularly in the  $+1.5$ -ms condition. The reason for the asymmetry in the effect of an 80-ms onset asynchrony is unclear. Whilst no precautions were taken to eliminate fixed IIDs due to incorrect headphone position, the symmetry of the data for the other conditions suggest that no unintended IIDs were present. Similarly, the fact that listener NC also displays an asymmetry but in the opposing direction

suggests that the bias was not simply due to an asymmetry in the apparatus or experimental procedure. In addition to the across-subject variability in the matches made using the pure-tone pointer, listeners CBC and SP also displayed significant variability across the four replications in the 1.5-ms condition. Since listeners were able to repeat the target-pointer sequence as often necessary, this variability is perhaps more likely to reflect uncertainty as to the position of the 500-Hz component rather than trial-to-trial variation in the effect of the flanking components. The variability is unlikely to be due to these listeners occasionally matching to the complex rather than to the 500-Hz component, since an 80-ms delay in the onset of the 500-Hz component is sufficient for the component to be readily audible.

By contrast with the effect of onset asynchrony on the perceived lateral position of the 500-Hz component, this manipulation had no significant effect on the lateralization of the complex. Thus either onset asynchrony did not prevent the 500-Hz tone from contributing to the perceived lateralization of the complex, or the perceived lateralization of the complex was largely independent of whether or not the tone was present. The plausibility of the second account was tested as part of experiment 4, the results of which confirm that physically removing the 500-Hz tone has only a marginal effect on the perceived lateralization of the complex. Further research using a stimulus whose lateralization is more sensitive to the removal of energy is needed to determine whether onset asynchrony can affect the lateralization of both of the corresponding images.

The finding that the complex is lateralized further from the center when presented with an ITD of  $\pm 0.5$  ms than when presented with an ITD of  $\pm 1.5$  ms is not, qualitatively at least, inconsistent with current across-frequency integration models of lateralization such as those proposed by Stern *et al.* (1988) and by Shackleton *et al.* (1992). Both these models assume that image position depends upon the distribution of neural activity across a two dimensional (frequency-delay) array of coincidence detector units. Specifically, a measure of the total activity across frequency at each delay is determined, with variously the peak or centroid of this measure along the delay axis used as an estimate of the image position. In common with other coincidence detector based models, there are assumed to be fewer units sensitive to large interaural delays than there are to small delays. Thus although increasing the ITD from 0.5- to 1.5-ms shifts the local peak in activity along the delay axis further from the origin, the magnitude of this peak is reduced, thereby reducing its contribution to the calculation of the centroid. At the same time the (smaller) peak in activity favoring the opposing side of the head will be closer to the center and will therefore have increased in magnitude. It is a matter for further investigation whether the resulting shift in the centroid can quantitatively account for the observed disparity between the positions of the 0.5- and the 1.5-ms interaurally delayed complexes.

### III. EXPERIMENT 2

The results of experiment 1 showed that when the onset of the center component of an interaurally delayed tonal

complex was delayed by 80 ms relative to that of the other components, then the asynchronous component was generally perceived either on, or shifted toward, the opposing side of the head to that of the complex. One interpretation of these results is that the auditory system is able to combine interaural-timing information selectively across frequency. In the second experiment the onset asynchrony of the 500-Hz component was varied parametrically to determine the minimum asynchrony required for a measurable displacement of the delayed component from the complex.

#### A. Procedure

The matching procedure and stimuli were similar to those used in experiment 1. Because there was no significant effect of onset asynchrony on the position of the flanking complex in experiment 1, in this experiment matches to the complex were only made in the 0-ms asynchrony condition. These data were collected during the first 12 trials with matches to the 500-Hz component made during the remaining trials. By contrast with experiment 1, listeners were only required to perform a single match on each trial.

The duration of the target stimulus was always 400 ms, with the 500-Hz tone being delayed with respect to the flanking complex by either 0, 20, 40, or 80 ms. All components were gated on with a 10-ms raised-cosine attack and gated off synchronously with a 190-ms raised-cosine decay. The use of an exponential gating envelope was abandoned since the results of subsequent practice sessions indicated that it had no noticeable effect on perceptual fusion of the target complex. Again, two pointer stimuli were used having the same amplitude envelope as used for the target. The inter-stimulus intervals used in the target-pointer sequence were increased relative to the first experiment, the target-target and pointer-pointer intervals being set to 150 ms, while the target-pointer interval was 200 ms. These adjustments were introduced in order to compensate for the decrease in the effective interstimulus intervals resulting from the switch to a raised-cosine amplitude envelope. The levels of components of the target stimuli were increased to 58 dB SPL.

The reported results for each listener were gathered in a single 60-trial session lasting approximately 50 min. For the first 12 trials listeners were presented with a synchronous target having an ITD of  $\pm 1.5$  ms (six of each at random) and were required to match its position using the complex pointer. In the remaining 48 trials the delay of the 500-Hz tone was varied parametrically (6 repeats  $\times$  4 delays  $\times$  2 ITDs) and its position matched using the pure-tone pointer. Prior to data collection each listener was run on a short practice session (comprising one presentation of each condition) to familiarize them with the stimuli and procedure.

#### B. Results

The data for each listener with error bars denoting one standard error of the mean are shown separately in Fig. 4. Filled symbols denote matches made using the complex pointer, open symbols matches made using the pure-tone pointer. Squares denote that the target was presented with an ITD of  $+1.5$  ms, circles, that the target was presented with an ITD of  $-1.5$  ms.

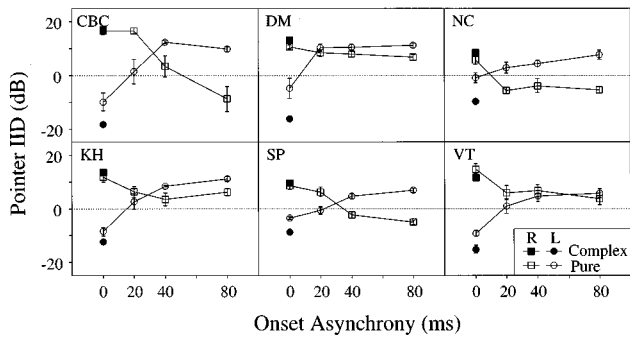


FIG. 4. Mean value of pointer IID ( $\pm 1$  s.e. across six repetitions) as a function of the onset-time delay of the 500-Hz component in experiment 2. Filled symbols denote matches made using the complex pointer, open symbols matches made using the pure-tone pointer. Squares denote that the target was presented with an ITD of +1.5 ms, circles, that the target was presented with an ITD of -1.5 ms.

The effect of onset asynchrony on the perceived lateralization of the 500-Hz tone was tested by means of a three-way analysis of variance, the factors being listener (6), size of asynchrony (4) and ITD (2). In order to compare the results for the two directions of interaural delay, the values of IID obtained in the -1.5-ms conditions were multiplied by -1. The main effects of listener, size of asynchrony and direction of interaural delay were all significant ( $F_{5,240}=13.38$ ,  $p<0.0005$ ;  $F_{3,240}=12.88$ ,  $p<0.0005$ ; and  $F_{1,240}=10.59$ ,  $p<0.005$ , respectively).

While visual inspection of the data presented in Fig. 4 clearly suggests that an asynchrony of 40 ms has a profound effect on the lateralization of the 500-Hz component for most listeners and conditions, this effect was not statistically significant averaged over listeners and direction of ITD (planned comparison,  $p>0.6$ ). The explanation for this is probably the variability in the matches, particularly for listener CBC. The difference between the 0- and 80-ms condition was highly significant (planned comparison,  $p<0.0005$ ). All listeners display evidence of a left-right asymmetry with respect to matches made using the pure-tone pointer, with much greater separation of the 500-Hz component (and less variability in the matches) when the target complex was presented with an ITD of -1.5 ms than when the ITD was +1.5 ms. The asymmetry with respect to direction of interaural delay is reflected in the fact that there is a significant two-way interaction between direction of delay and the size of the asynchrony ( $F_{3,240}=10.78$ ,  $p<0.0005$ ).

The data corresponding to the 0-ms asynchrony condition (obtained with both the complex and pure-tone pointers) was subjected to a three-way analysis of variance comparing the effects of listener, ITD and pointer type. All three effects were significant ( $F_{5,120}=19.33$ ,  $p<0.0005$ ;  $F_{1,120}=10.16$ ,  $p<0.005$ ; and  $F_{1,120}=43.66$ ,  $p<0.005$ , respectively).

For the five listeners who also participated in experiment 1, the mean IIDs obtained with the complex pointer were similar across the two experiments, the rms difference being 3.2 dB, while the maximum disparity was 5.8 dB (listener VT, ITD=+1.5 ms). However, there was substantial variability in matches made using the pure-tone pointer across the two experiments. In the synchronous onset case, three

listeners (CBC, DM, and NC), had disparities exceeding 10 dB with the corresponding pointer IIDs in the present experiment being closer to zero. In the 80-ms asynchrony condition, CBC and NC again had disparities exceeding 10 dB while the maximum disparity for the remaining listeners did not exceed 5 dB.

### C. Discussion

The results confirm those of the first experiment in that (i) the synchronous complex presented with an ITD of 1.5 ms is lateralized toward the leading ear and (ii) onset asynchrony has a clear effect on the lateralization of the 500-Hz tone. The finding that the effect of onset asynchrony flattens out somewhere between 40–80 ms is consistent with the results obtained in vowel perception where onset asynchronies of around 30 ms are sufficient to prevent a harmonic from contributing to the first formant frequency of a vowel (Darwin, 1984; Roberts and Moore, 1991).

The finding of an effect of onset asynchrony in a lateralization-matching paradigm (experiments 1 and 2) contrasts with the results of interference paradigms in which reliable effects have only been observed when the flanking sounds are continuous (Trahiotis and Bernstein, 1990; Bernstein and Trahiotis, 1995). There are a number of factors that may play a role in reconciling the results of the two paradigms. First, the fact that the delayed component was generally lateralized toward the side of the head receiving the lagging signal does not preclude the possibility of some residual interference between it and the flanking components. Indeed, the results of both experiments suggest that an asynchrony of 80 ms was insufficient to entirely remove the effect of the flanking tones, at least for some listeners. Second, while previous studies have failed to show consistent effects of asynchronies with noncontinuous interferers, there is evidence that some listeners can make use of such a cue. For example, Woods and Colburn (1992) found that two of their four listeners exhibited significantly less interference when the onset of the pure-tone target was delayed, than when it was gated synchronously with the interferer tones. It is possible that the present paradigm is more effective in encouraging listeners to exploit the presence of an onset asynchrony. Third, the magnitude of the interaural delay used in the present experiments was greater than that that would arise for naturally occurring sounds, and was such that the nominal lateralizations of the complex and segregated harmonic were on opposing sides of the head. Buell and Hafter (1991) reported that their own target-interferer combinations sometimes gave rise to multiple locations, particularly when the two tones had very different ITDs.

There was some indication that listeners were able to hear out the 500-Hz component in a different lateral position to the complex even when they were gated synchronously. By contrast, only listener VT showed strong evidence of perceiving the 500-Hz component in a different position to the complex in the corresponding condition of experiment 1. Two factors which may have contributed toward listeners' ability to hear out the 500-Hz component in the present experiment were the greater proportion of trials in which that component was asynchronous, and the inclusion of trials

with asynchronies less than 80 ms. It is possible that as a result listeners may have been made more aware of the existence of a weak image corresponding to the 500-Hz component. The extent to which the lateralization of the 500-Hz component was affected by the presence of the flanking components, both when synchronous and when delayed by 80 ms, was investigated further in experiment 4.

#### IV. EXPERIMENT 3

In experiments 1 and 2 it was found that delaying the onset of one component of an interaurally delayed complex resulted in two images; a complex image lateralized on the side of the head receiving the leading signal, and a pure-tone image lateralized toward the position that the asynchronous component would have occupied had the flanking components not been present. The objective of the present experiment was to investigate the extent to which a second cue to source segregation, mistuning, could similarly lead to the perception of images in different lateral positions. Evidence that harmonic relationships may influence the across-frequency processing of binaural information was provided by Buell and Hafter (1991) who found that binaural interference between a target and distractor tone was only observed when the two tones were harmonically related. The maximum mistuning employed in the present experiment was 6%, a choice based on the finding of Moore *et al.* (1986) that a mistuning of 1.3%–2% is sufficient for a low numbered component of a harmonic complex to be heard out as a separate tone.

##### A. Procedure

The procedure was identical to that used in experiment 2, but with mistuning replacing onset asynchrony as the variable parameter. Seven values of mistuning were used: 0%,  $\pm 1\%$ ,  $\pm 3\%$ , and  $\pm 6\%$ . Data for the two directions of mistuning were collected in separate sessions each lasting approximately 45 min. All listeners received the positive mistuning condition in the first session, followed by the negative mistuning condition seven to nine days later. As with experiment 2, the target could be presented with an interaural time difference of either plus or minus 1.5 ms. Each mistuning was presented six times in a random order determined by the computer. All stimuli were of 300-ms duration, and were gated on and off with raised-cosine envelopes of length 10 and 190 ms, respectively. The level of presentation of the stimuli was the same as in experiment 2. The target–target, target–pointer, and pointer–pointer interstimulus intervals were each 100 ms. For trials involving a pure-tone pointer, the frequency of the pointer was adjusted to match that of the mistuned 500-Hz component.

##### B. Results

The mean pointer IIDs corresponding to the negative and positive mistuning conditions are shown separately for each listener in Figs. 5 and 6, respectively, with error bars denoting one standard error of the mean. The conventions for

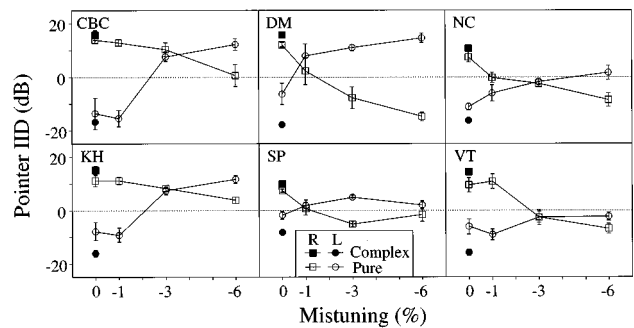


FIG. 5. Mean value of pointer IID ( $\pm 1$  s.e. across six repetitions) as a function of the negative mistuning of the 500-Hz component in experiment 3. Filled symbols denote matches made using the complex pointer, open symbols matches made using the pure-tone pointer. Squares denote that the target was presented with an ITD of +1.5 ms, circles, that the target was presented with an ITD of -1.5 ms.

the individual graphs are the same as for experiment 2 but with mistuning replacing onset asynchrony as the variable parameter.

The data were subjected to a four-way analysis of variance with each of the factors having significant effects (listener:  $F_{5,480}=19.34$ ,  $p<0.0005$ ; direction of mistuning:  $F_{1,480}=4.73$ ,  $p<0.05$ ; direction of ITD:  $F_{1,480}=17.77$ ,  $p<0.0005$ ; and magnitude of mistuning:  $F_{3,480}=239.04$ ,  $p<0.0005$ ).

Consider first the effects of negatively mistuning the 500-Hz component (Fig. 5). The small size of the standard error bars associated with the mean IIDs obtained with the complex pointer (eight less than 1 dB, four less than 2 dB) indicate that listeners lateralized the complex consistently across trials. In the case of matches to the pure tone, the standard errors are generally somewhat greater, exceeding 3 dB in nine of the 48 cases. Closer inspection of the individual matches for these nine cases, however, reveals that in six of the nine cases the standard error is exaggerated by a single match bearing little similarity to the other five. Thus although there is greater variability in the pure-tone data, listeners generally lateralize the pure-tone target consistently for a given condition, thereby justifying the use of mean

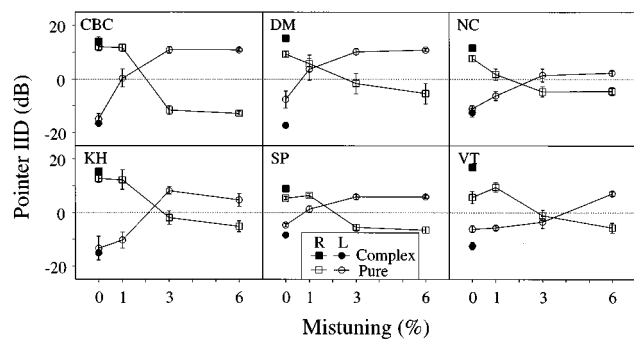


FIG. 6. Mean value of pointer IID ( $\pm 1$  s.e. across six repetitions) as a function of the positive mistuning of the 500-Hz component in experiment 3. Filled symbols denote matches made using the complex pointer, open symbols matches made using the pure-tone pointer. Squares denote that the target was presented with an ITD of +1.5 ms, circles, that the target was presented with an ITD of -1.5 ms.

pointer IID as an appropriate measure with which to examine the effect of mistuning.

Five of the six listeners display a monotonic pattern of behavior with the displacement of the mistuned tone toward the lagging side of the head increasing with increases in the size of the mistuning. Surprisingly this pattern is violated by listener SP for whom the displacement decreases at the maximum value of mistuning. The data for listeners DM, NC, and SP show a significant effect of a  $-1\%$  mistuning averaged over the two directions of ITD (planned comparisons,  $p < 0.05$ ). By  $-3\%$ , all listeners show a significant effect (planned comparisons: CBC, DM, KH, NC, and SP  $p < 0.0005$ , VT  $p < 0.001$ ). For all listeners other than SP, a mistuning of around  $-6\%$  appears sufficient to remove almost all the influence of the flanking tones for at least one direction of ITD. However, only for listener DM does a mistuning of  $-6\%$  appear sufficient to remove the effect of the flanking tones for both directions of ITD.

With regards to positive mistunings (Fig. 6), there are again nine cases in which the standard error of the mean (for matches made using the pure-tone pointer) exceeds 3 dB. Five of these can be accounted for by a single uncharacteristic match leaving four cases (one for listener CBC, three for listener DM) for which the individual matches are somewhat inconsistent. It therefore appears that the use of mean pointer IID is again a suitable measure.

The general pattern of results is the same as that obtained in the negative mistuning condition although positive mistunings appear somewhat more effective. Three listeners (CBC, DM, and NC) show a significant effect of a mistuning of just  $1\%$  (planned comparisons,  $p < 0.05$ ), with the effect of a positive mistuning asymptoting for all six listeners somewhere between  $3\%$  and  $6\%$ .

As in experiment 2, an analysis of variance was performed comparing the matches for the complex and pure-tone pointers in the  $0\%$  mistuning condition. The four factors were listener, direction of mistuning, direction of ITD and pointer type. As suggested by visual inspection of the data, the effect of pointer type was significant ( $F_{1,240} = 84.76$ ,  $p < 0.0005$ ).

### C. Discussion

The data support Buell and Hafter's finding that only tones which are harmonically related to a target tone strongly influence its lateralization. Indeed, the lateralization percept appears particularly sensitive to mistuning, with some listeners showing an effect for mistunings of  $\pm 1\%$  while for most listeners a mistuning of  $\pm 3\%$  is sufficient to reduce substantially the contribution of the flanking tones. It is not clear how the results of the present experiment can be reconciled with those of Stellmack and Dye (1993) which failed to show an effect of harmonicity. However, it is worth noting that in the seven-component condition of their experiment, the 753-Hz target was flanked by interferers at 700 and 800 Hz. Thus it is likely that significant monaural interference was taking place.

The disparity observed in the previous two experiments between the mean matches associated with the complex and pure-tone pointers when the 500-Hz component is unper-

turbed was also observed in this experiment. The tendency for the IID of the pure-tone pointer to be less than that for the complex may have been due to some listeners hearing out the central component even when it was harmonically related to the flanking tones. However, the disparity may also be due to the fact that the two pointer stimuli require different values of ITD to achieve a given lateral displacement. Inspection of the data reveals that the mean IID of the pure-tone pointer rarely exceeds the value attained in the  $0\%$  mistuning conditions. This suggests that the value of IID employed in the  $0\%$  mistuning condition may be sufficient for the pure-tone pointer to be fully lateralized. Differences in the possible "calibrations" of the two pointers were examined in the following experiment.

## V. EXPERIMENT 4

This experiment was undertaken in order to resolve a number of issues relating to the results of the previous experiments. First, it was observed that the mean IIDs obtained with the complex and pure-tone pointers frequently differed even when the 500-Hz component was unperturbed. However, since the two pointers were spectrally distinct, it is not clear whether these differences were due to listeners being able to hear out and independently lateralize the 500-Hz component, or were simply a consequence of the fact that the different pointer stimuli may have required different IIDs in order to illicit the same subjective lateral position. Second, since no comparisons were made between the perceived lateral position of the asynchronous 500-Hz component, and that of a 500-Hz tone in isolation, it is not clear whether an 80-ms asynchrony was sufficient for complete perceptual segregation. Third, the results of experiment 1 suggested that the perceived lateralization of the complex was not significantly affected by the relative onset of the 500-Hz tone. However, the experiment did not determine whether this was due to the ineffectiveness of onset asynchrony in preventing the 500-Hz tone from contributing to the lateralization of the complex, or to the fact that the 500-Hz tone had negligible influence on the lateralization of the complex.

### A. Procedure

The procedure was essentially the same as that used in experiments 2 and 3 with listeners having to adjust the lateral position of a given pointer stimulus to match that of a corresponding target image. Four different target stimuli were used: a six-component complex ( $C$ ) comprising harmonics 2 to 4 and 6 to 8 of 100 Hz, a seven-component complex ( $CT$ ) comprising harmonics 2 through 8, the same seven-component complex but with the onset of 500-Hz tone delayed by 80 ms ( $CT_d$ ), and a 500-Hz tone in isolation ( $T$ ). Each target was presented with ITDs of both plus and minus 1.5 ms. Matches to the first three target stimuli were made using both the complex and pure-tone pointers, whilst matches to the isolated 500-Hz tone were made using the pure-tone pointer only.

The two pointers, the trial structure, the amplitude of each component and the method of gating were the same as those used in experiment 2. All components other than the asynchronous 500-Hz tone had a duration of 400 ms, the



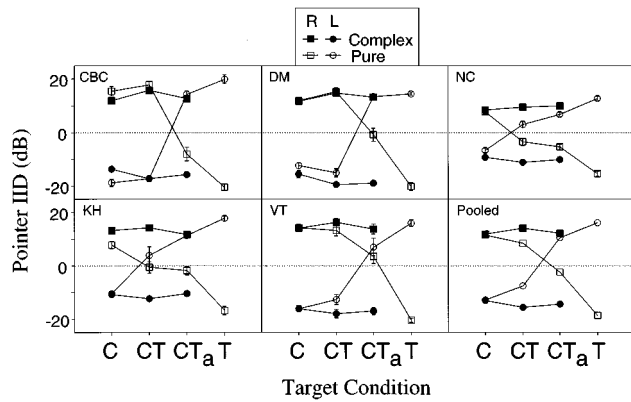


FIG. 7. Mean value of pointer IID ( $\pm 1$  s.e. across five repetitions) for the four target conditions of experiment 4. Filled symbols denote matches made using the complex pointer, open symbols matches made using the pure-tone pointer. Squares denote that the target was presented with an ITD of +1.5 ms, circles, that the target was presented with an ITD of -1.5 ms.

asynchronous tone having a duration of 320 ms due to the 80-ms delay. The reported data were collected over two 70-trial sessions each lasting approximately 1 h. The structure of the two sessions was identical with listeners required to make a total of five matches to each of the 14 conditions described above (7 target–pointer pairs  $\times$  2 interaural delays); the 70 stimuli were presented in a random order. Five listeners were used in this experiment, all of whom had participated in experiments 2 and 3. Listener SP was unavailable.

## B. Results

The mean values of pointer IID for the four types of target together with error bars denoting one standard error of the mean are shown separately for each listener in Fig. 7. Included in the figure is a summary of the data pooled over listeners. Squares denote that the target was presented with an ITD of +1.5 ms, circles that the target ITD was -1.5 ms. Filled symbols are used to denote matches made using the complex pointer.

The data relating to the six-component target (C) and synchronous seven-component target (CT) were subjected to a four-way analysis of variance, the factors being listener, target condition, pointer type and direction of ITD. All four main effects were significant ( $F_{4,360}=110.02$ ,  $p<0.0005$ ;  $F_{1,360}=80.20$ ,  $p<0.05$ ;  $F_{1,360}=81.83$ ,  $p<0.0005$ ; and  $F_{1,360}=4.76$ ,  $p<0.05$ , respectively). There was a significant two-way interaction between target condition and pointer type ( $F_{1,360}=67.25$ ,  $p<0.0005$ ). The matches associated with both the pure-tone pointer and complex pointer differed significantly across the two target conditions (planned comparisons:  $p<0.0005$  in both cases).

A similar four-way analysis of variance was performed on the data for the synchronous and asynchronous target conditions with all four main effects again proving to be significant (listener:  $F_{4,360}=51.53$ ,  $p<0.0005$ ; condition:  $F_{1,360}=284.75$ ,  $p<0.0005$ ; pointer type:  $F_{1,360}=788.43$ ,  $p<0.0005$ ; and direction of interaural delay:  $F_{1,360}=6.96$ ,  $p<0.01$ ). There was a significant two-way interaction between target condition and pointer type ( $F_{1,360}=189.34$ ,

$p<0.0005$ ) reflecting a shift of the pure tone toward the leading ear in the asynchronous onset condition.

Visual inspection of the data suggests that the effect of onset asynchrony on the position of the pure tone was more pronounced in the negative ITD condition. This asymmetry was reflected by a significant three-way interaction between direction of interaural delay, target condition and pointer type ( $F_{1,360}=16.69$ ,  $p<0.0005$ ).

To test whether the perceived lateral position of the asynchronous 500-Hz component was influenced significantly by the flanking complex, a three-way analysis of variance (listener  $\times$  condition  $\times$  interaural delay) was performed on the pure-tone data for the asynchronous and pure-tone target conditions. The three main effects were highly significant (listener:  $F_{1,180}=8.17$ ,  $p<0.0005$ ; condition:  $F_{1,180}=226.65$ ,  $p<0.0005$ ; ITD:  $F_{1,180}=14.41$ ,  $p<0.0005$ ).

## C. Discussion

Onset asynchrony was again shown to have a significant effect on the perceived lateralization of the 500-Hz tone, even for the two listeners who perceived the tone in a different position to the complex in the synchronous onset condition. It does appear, however, that the lateral position of the 500-Hz tone was still influenced by the presence of the flanking tones even when it was gated asynchronously.<sup>2</sup> In particular, the complex appears to have a “pulling” effect resulting in the 500-Hz component being lateralized significantly closer to the mid-line than the pure-tone control. This result demonstrates explicitly that the presence of extraneous energy can affect the perceived lateral position of a segregated frequency component. However, it is possible that the residual interference may be a within-channel rather than an across-frequency phenomenon, perhaps resulting from the presence of combination tones. The results of experiment 2 suggest that increasing the asynchrony beyond 80 ms would result in relatively little additional displacement of the 500-Hz tone. Again, it is not clear why the effect of asynchrony was asymmetric with respect to the direction of the ITD, although the extent of the asymmetry was reduced relative to experiment 2.

The matches obtained with the complex pointer suggest that listeners generally perceived the synchronous seven-component complex further from the center than either the asynchronous seven-component complex or the six-component complex. This finding is consistent with the idea that the 500-Hz component made a small contribution to the lateralization of the complex image, and that this contribution was reduced when the 500-Hz component was asynchronous. The fact that the 500-Hz component had only a small effect on the position of the complex is consistent with the results of a study by Dye (1990) which showed that listeners’ ability to discriminate the direction of an interaural time difference conveyed by the components of a complex was little affected by the presence of a single diotic interferer.

The data for listeners NC and KH suggests that both listeners perceived the 500-Hz component in a different lateral position to the complex even when the 500-Hz component was gated synchronously with the flanking tones. The

TABLE I. Effective interaural phase difference of each component of the target complex for the four values of target ITD used in experiment 5. Negative phases denote that the nominal lateralization of the component is toward the ear receiving the lagging signal.

Freq. (Hz)	Period (ms)	Effective interaural phase difference			
		ITD=1.0 ms	ITD=1.25 ms	ITD=1.50 ms	ITD=2.50 ms
200	5.00	72°	90°	108°	180°
300	3.33	108°	135°	162°	-90°
400	2.50	144°	180°	-36°	0°
500	2.00	180°	-135°	-90°	90°
600	1.67	-144°	-90°	-144°	180°
700	1.43	-108°	-45°	18°	-90°
800	1.25	-72°	0°	72°	0°

fact that these listeners perceived images in different lateral positions in the absence of monaural cues to segregation is not in itself surprising. For example, Blauert (1978) noted that when a target band of an otherwise diotic broadband noise signal was interaurally delayed, experienced listeners were able to perceive two images: one laterally displaced in the direction of the ITD, and the other near the mid-line. Similarly, the dichotic pitch phenomena associated with rapid transitions in interaural phase over a narrow frequency region (e.g., Klein and Hartmann, 1981) demonstrate the interaural phase information alone is sufficient in some circumstances to elicit the percept of multiple images in different lateral positions. In the present experiment perceptual segregation of the 500-Hz component may have been facilitated by the large disparity between the nominal lateralization of the 500-Hz component and that of the complex. However, since there were also significant disparities between the nominal lateralizations of some of the other components and the complex, it seems unlikely that the ITD alone was leading to perceptual segregation of the 500-Hz component. A second contributory factor may have been the use of a 500-Hz tone as a pointer stimulus (e.g., Plomp and Mimpen, 1968). While the pointer stimulus was always presented after the target, it is possible that repeated exposure to the 500-Hz component over the course of the experiment may have served to direct listeners' attention to the presence of the corresponding component of the complex.

## VI. EXPERIMENT 5

The lateralization data obtained in the previous experiments are consistent with the idea that the lateral position of a multitone complex is determined by integrating binaural information across frequency in a similar fashion to that proposed for noise stimuli.

However, it is also possible that lateralization of the complex is derived from a weighted average of the nominal image positions of the individual components. For example, when the seven-component complex is interaurally delayed by 1.5 ms, only three of the seven components have interaural phase differences that would lead to them being lateralized on the lagging side of the head, while the other four would be lateralized on the leading side. To examine whether the lateralization of the complex was affected by the nominal lateralization of its constituent components, the perceived lateral position of the complex was measured for four

different values of interaural delay ranging in magnitude from 1.0 and 2.5 ms. Varying the size of the ITD between these two values has the effect of changing the nominal lateralizations of the individual components while ensuring that true ITD always corresponds to the same side of the head. Table I shows the effective interaural phase difference of each component for the four values of ITD that were used in this experiment.

If the lateral position of a tonal complex is determined by first determining the nominal lateralizations of the individual components and then averaging these across frequency, then the four ITDs should result in a substantial variation in the lateralization of the complex. For example, with an ITD of 1.0 ms, the three highest frequency components have nominal lateralizations favoring the ear receiving the lagging signal, while the lateralization of the 500-Hz component is ambiguous. Therefore, given that the auditory system weights energy around 600 Hz more heavily for the purposes of lateralization (Raatgever, 1980), an ITD of 1.0 ms might be expected to lead to the image being perceived on the side of the head receiving the lagging signal. On the other hand, if the auditory system weights more heavily that delay that is consistent across frequency, then for all four ITDs the complex should be lateralized clearly on the side of the head receiving the leading signal. Experiment 5 also serves to provide data about how the perceived lateralization of the complex varies as a function of its interaural delay.

### A. Procedure

The target stimulus was always a seven-component complex consisting of the second through eighth harmonics of 100 Hz. All components were presented at 58 dB SPL, were gated on at the same time using a 10-ms raised-cosine attack, were sustained at a steady amplitude for 200 ms and were then gated off with a 190-ms raised-cosine decay. Four values of target ITD were used; 1.0, 1.25, 1.5, and 2.5 ms with the side to which the signal was leading divided equally over trials between left and right. On each trial listeners were required to match the lateral position of the target using a complex pointer identical to that used in Experiments 2 and 4. During the experiment each of the four ITDs were presented a total of 12 times (six trials for each of the two directions) in a random order. Data were collected for four of the six listeners who participated in experiment 2, the remaining two listeners, SP and NC, being unavailable.

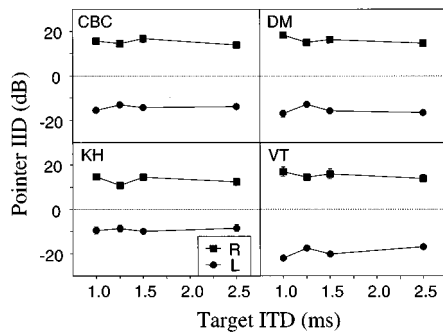


FIG. 8. Mean pointer ITDs ( $\pm 1$  s.e. over six replications) used in matching the lateral position a synchronous seven-component complex as a function of the magnitude of its ITD in experiment 5. Filled squares denote that the target was presented with a positive ITD, while filled circles denote negative ITDs.

## B. Results

The mean pointer ITDs corresponding to the four target ITDs are shown separately for each listener in Fig. 8. Filled squares denote that the target was presented with a positive ITD, while filled circles denote negative ITDs. The error bars represent one standard error of the mean. The horizontal axes show the value of target ITD in milliseconds while the vertical axes show the pointer IID.

For each value of ITD all four listeners consistently perceived the target clearly on the side of the head receiving the leading signal. The effect of ITD on perceived lateralization of the complex was analyzed over listeners by means of a three-way analysis of variance (listener  $\times$  direction of ITD  $\times$  magnitude of ITD). As in previous analyses, IIDs obtained in the left leading (i.e., negative ITD conditions) were multiplied by  $-1$  to allow a direct comparison between the two directions of ITD. There were significant effects of listener ( $F_{3,160}=38.45$ ,  $p<0.0005$ ) and magnitude of ITD ( $F_{3,160}=10.07$ ,  $p<0.0005$ ) but no significant effect of direction of interaural delay ( $F_{1,160}=1.21$ ,  $p>0.2$ ).

## C. Discussion

The four values of target ITD used in this experiment were chosen to investigate whether the lateralization of the target complex could be explained in terms of the weighted average of the nominal lateralizations of the individual components. As illustrated in Table I each value of ITD results in a different set of components being nominally lateralized on the side of the head receiving the leading signal. Indeed, in the case of an ITD of 2.5 ms only the 500-Hz component would be unambiguously lateralized on the leading side of the head, while two components would be lateralized on the lagging side. It is difficult to conceive how the obtained results could be explained in terms of a weighted average of the positions of the individual components. Rather, the data suggest that the perceived lateral position of a complex is determined from an integration of the binaural information across each active frequency channel.

Given that the lateral position of the complex was determined from an across-frequency integration of binaural information, the finding that the lateralization was relatively unaffected by changes in ITD from 1.0 to 2.5 ms may be due

to the fact that all four ITDs are significantly greater than the maximum naturally occurring ITD, the result being that the image was fully lateralized in all cases.

## VII. GENERAL DISCUSSION

These experiments have extended to periodic stimuli a result reported by Trahiotis and Stern (1989) for noise. Trahiotis and Stern asked listeners to match the lateral position of a bandpass noise centered on 500 Hz and delayed to one ear by 1.5 ms. They showed that a narrow-band noise was lateralized toward the lagging ear, but that as the bandwidth of the noise was increased, its perceived position shifted across toward the ear receiving leading signal. This displacement of the image toward the correct side of the head is thought to result from an emphasis of that delay that is consistent across frequency (Stern *et al.*, 1988; Shackleton *et al.*, 1992). Similarly, we have demonstrated that if the individual components of a periodic complex tone share a common interaural delay, then the perceived lateralization of the complex corresponds to that delay (experiments 1 and 4). In particular, the lateralization does not appear to depend explicitly upon the nominal lateralization of the individual components (experiment 5).

The experiments have also shown that when a component is perceptually segregated from a harmonic complex, either by delaying its onset relative to the remaining components, or by mistuning, then that component can be lateralized in a significantly different position to that of the remaining components. In the case of onset asynchrony, a delay of as little as 20–40 ms (experiment 2) was generally sufficient for the delayed component to be lateralized in a significantly different position to that of the parent complex. Similarly, mistuning the central component of the complex by 3% (experiment 3) resulted in that component being perceived on the opposing side of the head to the remaining components. These results suggest that spatial information may be combined selectively across frequency on the basis of auditory grouping cues and are therefore qualitatively consistent with models of auditory object formation such as that proposed by Woods (Woods, 1990; Woods and Colburn, 1992). For some listeners and conditions there was considerable variability in the matches to the 500-Hz component, even within the same experimental session. Since on each trial listeners were free to repeat the target–pointer sequence as often as necessary, the most plausible explanation for this variability is uncertainty as to the lateral position of the 500-Hz component.

It should perhaps not be surprising to find that the degree to which the spatial attributes of energy in one frequency region are affected by the presence of energy elsewhere depends in some way on a measure of their commonality. After all, features such as common onset time, shared fundamental and coherent amplitude modulation are consistent with the energy being produced by a single source and have been shown to play an important role in the perceptual fusion or segregation of components (Bregman and Pinker, 1978; Darwin, 1981; McAdams, 1982; Darwin, 1984; Moore *et al.*, 1985; McAdams, 1989; Bregman, 1990; Darwin and Ciocca, 1992). Indeed, the presence of grouping cues such as correlated amplitude modulation and common

onset has been shown to influence the presumed across-frequency integration of information underlying other interference paradigms (Grose and Hall, 1993; Moore and Bacon, 1993; Grose *et al.*, 1995).

The finding that the perceived lateral position of the asynchronous 500-Hz component was less fully lateralized than a corresponding pure-tone (experiment 4) provides direct evidence that the perceived lateral position of a segregated auditory object can be affected by the presence of extraneous energy. It is not clear whether the residual influence of the flanking components was due to the fact that the particular grouping cues used in the present experiments were insufficient to entirely eliminate the integration of binaural information across-frequency, or reflects a more general finding that grouping cues *per se* cannot prevent some degree of binaural interference. It is also possible that the residual influence of the flanking components may be due to within-channel rather than across-channel interactions. Clearly further work is needed to help clarify the extent to which grouping cues facilitate the independent lateralization of naturally occurring sounds.

An interesting question concerns the extent to which delaying the onset of, or mistuning, the 500-Hz component reduced its contribution to the lateral position of the complex itself. In the case of pitch perception, reductions in the contribution of a component to the pitch of the parent complex are observed with asynchronies and mistunings in excess of 80 ms and 3%, respectively (Darwin and Ciocca, 1992; Hukin and Darwin, 1995). Unfortunately, and as evidenced by the results of experiment 4, the contribution of the 500-Hz component to the lateral position of the complex was so minimal that a reliable assessment of the effect of segregation on the position of the complex could not be made.

To summarize, the present experiments support the view that the lateralization of broadband stimuli is determined by integrating binaural information across frequency. The results also suggest that the auditory system does not integrate information indiscriminately across frequency, but does so selectively on the basis of auditory grouping cues. Further experiments are required to determine whether the results generalize to more realistic values of ITD, and whether the residual influence of the complex on the perceived lateralization of the perturbed component can be further reduced by using larger perturbations and/or combining multiple cues.

## ACKNOWLEDGMENTS

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<sup>1</sup>For a given pointer IID, the absolute levels of the signals in the two ears ( $I_L$  and  $I_R$ ) were chosen in such a way as to maintain approximately constant loudness. To this end, the summed binaural loudness was assumed to be well described by the following empirical relationship (Zwicker and Zwicker, 1991):

$$L(I_L + I_R) = 0.54L(I_L) + L(I_R), I_L \leq I_R.$$

The monaural loudness,  $L(I)$ , was calculated using Steven's power law,  $L = kI^{0.3}$ .

<sup>2</sup>The differences in the extent of lateralization are unlikely to arise from the differences in the duration of the two stimuli (320 ms for the asynchronous tone versus 400 ms for the isolated tone). For example, Yost (1981) found no significant difference between lateralization data for a 100-ms duration 500-Hz tone, and that for a tone having a duration of 500 ms.

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