# Cross-frequency interactions in the precedence effect

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This paper concerns the extent to which the precedence effect is observed when leading and lagging sounds occupy different spectral regions. Subjects, listening under headphones, were asked to match the intracranial lateral position of an acoustic pointer to that of a test stimulus composed of two binaural noise bursts with asynchronous onsets, parametrically varied frequency content, and different interaural delays. The precedence effect was measured by the degree to which the interaural delay of the matching pointer was independent of the interaural delay of the lagging noise burst in the test stimulus. The results, like those of Blauert and Divenyi [Acustica **66**, 267–274 (1988)], show an asymmetric frequency effect in which the lateralization influence of a lagging high-frequency burst is almost completely suppressed by a leading low-frequency burst, whereas a lagging low-frequency burst is weighted equally with a leading high-frequency burst. This asymmetry is shown to be the result of an inherent low-frequency dominance that is seen even with simultaneous bursts. When this dominance is removed (by attenuating the low-frequency burst) the precedence effect operates with roughly equal strength both upward and downward in frequency. Within the scope of the current study (with lateralization achieved through the use of interaural time differences alone, stimuli from only two frequency bands, and only three subjects performing in all experiments), these results suggest that the precedence effect arises from a fairly central processing stage in which information is combined across frequency. 

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## INTRODUCTION

The precedence effect in binaural hearing refers to the dominance of earlier-arriving interaural cues, often associated with abrupt onsets, in determining sound source localization and intercranial sound image lateralization. Although there is a long history of research on the precedence effect (Zurek, 1987), one important question that has just begun to be addressed concerns the spectral spread of the effect.

Recent studies by Blauert and Divenyi (1988) and Divenyi (1992) examined the influence of a brief diotic leading sound on the discriminability of interaural delay of a brief lagging sound, with the leading and lagging sounds in different spectral regions. Their results showed strong interference with the interaural discrimination task (i.e., strong precedence effect) when the leading sound was lower in frequency than the lagging sound and little or no effect when the leading sound was higher in frequency than the lagging sound. Blauert and Divenyi (1988) interpreted these results as being consistent with the asymmetry of peripheral frequency analysis (upward spread of excitation). They acknowledged, however, that the lagging sound was always audible and that the spectral asymmetry must therefore lie in the interaural-delay domain—an effect they referred to as "localization masking."

Divenyi (1992) revised this interpretation by introducing the concept of "localization strength." According to this notion a leading sound that is high in localization strength—where localization strength is measured by sensitivity to interaural delay—would mask the localization information in a trailing sound more so than a leading sound that is low in localization strength.

Similar studies of cross-frequency precedence effects have been underway in our lab, and these have forced us also to consider the joint contribution of spectral and temporal effects. The present report describes these studies, which include an experimental approach to factoring out the influence of each variable (spectral difference or temporal order) in order to measure the influence of the other factor in isolation.

## I. GENERAL METHODS

The methods employed here are essentially the same as the pointer methods described by Shinn-Cunningham *et al.* (1993). All subjects in the experiments had normal hearing; three of the subjects were authors of the paper, while the remaining three subjects (in the first experiment) were paid undergraduates with no previous experience in binaural tasks. Listening under headphones, subjects adjusted an acoustic pointer to match the intracranial position of a test stimulus. By pressing keys on the keyboard of a computer terminal, subjects could switch between listening to the pointer (an ongoing train of noise bursts) and the test stimulus (also an ongoing train of noise bursts). The pointer and test stimuli always had similar spectral composition but different interaural temporal structure (described below). In addition, to help distinguish between the two trains, the pointer stimuli were presented at a rate of two per 1.5 s whereas the test stimuli were presented at two per second. The position of the pointer was varied by changing interaural delay in steps of 12.5, 25, or 50 $\mu$s in either direction, depending on which

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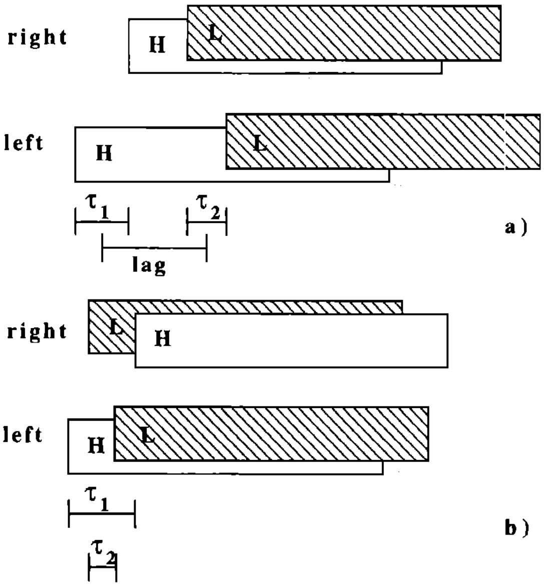


FIG. 1. Schematic diagram of stimuli. Binaural noise bursts with either high- (H) or low- (L) frequency content were presented with interaural time delays $\tau_1$ and $\tau_2$, with a delay (called lag) between mean onsets. (a) Diagram showing bursts when lag is 1 ms (experiments 1 and 3). (b) Diagram showing bursts when lag is 0 ms (experiment 2). In this case, *t*2 refers to the interaural delay in the L stimulus.

key was depressed. The magnitude of the pointer's interaural delay was limited to 1000 $\mu$s. When satisfied with a match, the subject terminated the trial, causing the final value of pointer interaural delay to be stored along with the parameters of the test stimulus. Feedback was provided to the subjects after every trial by printing to the screen the values of the initial and trailing burst ITDs and the interaural delay of the pointer stimulus.

The test stimuli were brief bandpass noise bursts presented as a pair of two binaural bursts, as shown in Fig. 1. Figure 1(a) shows the test stimuli used in experiments 1 and 3, while Fig. 1(b) shows the test stimuli used in experiment 2. Each noise burst in the test stimuli originated as digital white noise that was then spectrally filtered and temporally windowed. The nominal bandwidth of the filter was 300 Hz and the rejection rates were at least 20 dB/oct. The time window, a 3-ms Hanning function, was applied to a segment of the narrow-band noise to form a burst. The center frequencies of the narrow-band noise bursts were either 450 Hz, termed the "low" or L stimulus, or 1250 Hz, the "high" or H stimulus. A test stimulus was constructed by summing two binaural bursts, with the onset of one lagging that of the other. In most cases this lag was 1 ms [Fig. 1(a)], a value which leads to a strong precedence effect for broadband noise bursts in similar experiments (Shinn-Cunningham *et al.*, 1993). In one experiment, there was no lag between bursts [i.e., the lag was zero; see Fig. 1(b)]. Because the durations of individual bursts were 3 ms, the stimuli overlapped in time for both values of lag. Leading and lagging binaural bursts were always independent samples that were individually scaled to achieve the desired level (an rms of 87 dB SPL for most cases). Further, within a train of stimuli fresh noise samples were used in each burst. The lateral position of the test stimulus was varied by imposing interaural delays $\tau_1$ and $\tau_2$, respectively, on the leading and lagging bursts.

The pointer stimulus was designed to be as similar in quality as possible to the test stimulus. It was composed of the same L and H stimuli for leading and lagging bursts, with the same lag between them, but with equal interaural delays for leading and lagging bursts. This interaural delay was adjusted by the subject to match the pointer's intracranial position to that of the test stimulus.

The measure of the precedence effect described by Shinn-Cunningham *et al.* (1993) was used here as well. According to the descriptive model outlined in that paper, the precedence effect is measured by a parameter **c** that weights the contributions of the leading and lagging interaural delays:

$$\alpha = \mathbf{c}\tau_1 + (1-\mathbf{c})\tau_2, \qquad (1)$$

where $\alpha$ is the average lateral position of the composite image as measured by the adjusted interaural delay of the pointer. In that paper, **c** was shown to depend upon a number of factors for wideband noise bursts, including the interburst lag, the burst level, and the difference of $\tau_1$ and $\tau_2$. In the present paper, the main effect to be examined is the dependence of **c** on noise-burst center frequency.

## II. EXPERIMENT 1: SEQUENTIAL BURSTS WITH EQUAL LEVELS

### A. Methods

Four subjects (RC, JG, SN, and DL) matched the positions of test stimuli that used all combinations of $\tau_1$ and $\tau_2$ from the set [−500, −150, 0, 150, 500] $\mu$s. This resulted in a total of 25 matches per run. Each run was repeated three times by each subject for each condition. For reasons of speed, two later subjects (PZ and BGSC) used combinations of $\tau_1, \tau_2$ from the smaller set [−150, 0, 150] $\mu$s (leading to nine matches per run), and replicated each run twice. Within a run all other stimulus parameters (noise-burst center frequencies, levels, lag) were fixed. All combinations of L and H stimuli in the leading and lagging positions were tested, leading to four conditions. Thus the initial four subjects performed 12 runs of 25 matches, while the later two subjects performed 8 runs of 9 matches. Every initial and trailing burst was scaled to achieve an rms of 87 dB SPL.

### B. Results

Regression analysis was performed on the pointer interaural delay for each of the four frequency conditions with $\tau_1$ and $\tau_2$ as variables. In the regression analysis, the least-square error solution is found for regression coefficients $r_1$, $r_2$, and $k$, given the equation

$$\alpha = r_1\tau_1 + r_2\tau_2 + k. \qquad (2)$$

If the proposed model (in which pointer interaural delay is a linear combination of $\tau_1$ and $\tau_2$ with constant **c**) holds, one or both of the variables should account for most of the variance in pointer interaural delay measurements. Further, the regression coefficients $r_1$ and $r_2$ should equal **c** and $1-\mathbf{c}$, respec-

TABLE I. Summary of regression analysis results for equal-level, precedence-effect experiment, with $\tau_1$ and $\tau_2$ as variables. Data averaged across six subjects.

| Frequency condition | $k$ (constant term) | $r_1$ ($\tau_1$ coefficient) | $r_2$ ($\tau_2$ coefficient) | Sum of coefficients | $R$ |
|---|---|---|---|---|---|
| H–L | −0.001 | 0.54 | 0.40 | 0.94 | 0.8198 |
| L–L | 0.017 | 0.77 | 0.12 | 0.89 | 0.9072 |
| H–H | 0.005 | 0.87 | 0.08 | 0.95 | 0.9597 |
| L–H | 0.013 | 0.90 | 0.08 | 0.97 | 0.9701 |

tively, and the constant $k$ should be near zero. Results (shown in Table I) were consistent with model predictions. In all conditions, $\tau_1$ and $\tau_2$ were both highly and positively correlated with the perceived lateral position of the test stimuli and accounted for most of the variability in $\alpha$ ($R > 0.82$). In addition, the coefficients $r_1$ and $r_2$ sum to approximately one for all four cases, and the constant terms are near zero. Rank-ordering the $r_1$ coefficients (which estimates **c**) shows that the precedence effect was weakest for the H–L condition, moderate for the L–L condition, and strongest (and approximately equal) in the L–H and H–H conditions. These trends can also be seen by examining Fig. 2, which plots $\alpha$ (the interaural delay of the pointer) as a function of $\tau_2$ (with $\tau_1$ as a parameter) for data taken with the larger stimulus set. The plotted values are averaged across subject. Each frequency condition is shown in a separate panel. The pointer interaural delay shows a strong dependence on $\tau_2$ in the H–L condition and a weaker dependence on $\tau_2$ in the L–L condition. For the L–H and H–H conditions, $\alpha$ is nearly equal to $\tau_1$ and shows only a slight dependence on $\tau_2$. If **c** were independent of $\tau_1$ and $\tau_2$, these plots would be straight lines with slopes of $(1-\mathbf{c})$, with intercepts of $\mathbf{c}\tau_1$.

In order to test the significance of the differences across frequency conditions seen in Fig. 2 and of any additional factors, a multiway ANOVA was performed on $\alpha$ for the four subjects RC, JG, SN, and DL. Factors in the ANOVA were frequency condition, $\tau_1$,$\tau_2$, and subject, including up to three-way interactions. The results of this analysis are shown in Table II. Many effects reached significance at an extremely high level. As expected on the basis of the regression

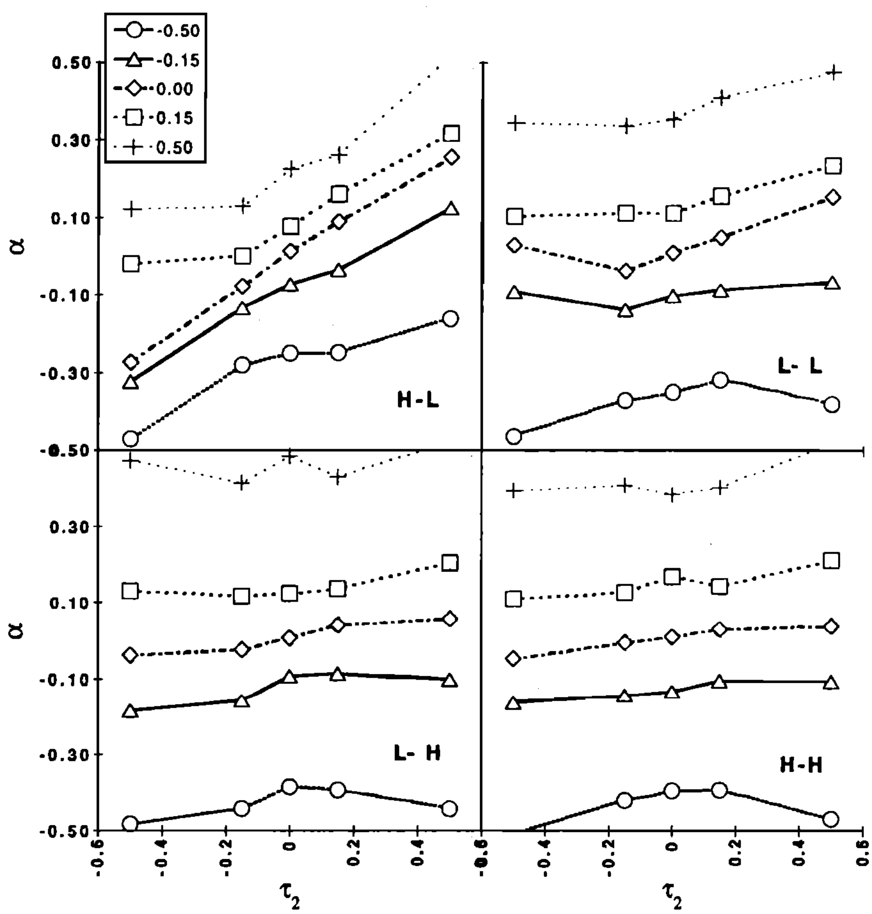


FIG. 2. Interaural delay of the pointer ($\alpha$) as a function of $\tau_2$, the interaural delay of the lagging burst in the test stimuli. The interaural delay of the leading burst ($\tau_1$) is shown parametrically. Each panel shows results for one of the four frequency conditions averaged across subjects.

TABLE II. Summary of multiway ANOVA results on $\alpha$ for equal-level, precedence-effect experiment with subject, frequency condition, $\tau_1$, and $\tau_2$ as factors, and including up to three-way interactions. Data for four subjects.

| Factor | $df$ | Sum squares | Mean square | $F$ ratio | Prob. |
|---|---|---|---|---|---|
| Frequency | 3 | 0.910 | 0.030 | 3.665 | 0.012 |
| $\tau_1$ | 4 | 79.478 | 19.870 | 2401.800 | <0.0001 |
| $\tau_2$ | 4 | 3.826 | 0.956 | 115.600 | <0.0001 |
| Frequency$\times\tau_1$ | 12 | 2.636 | 0.220 | 26.553 | <0.0001 |
| Frequency$\times\tau_2$ | 12 | 2.579 | 0.215 | 25.977 | <0.0001 |
| $\tau_1\times\tau_2$ | 16 | 0.779 | 0.049 | 5.884 | <0.0001 |
| Frequency$\times\tau_1\times\tau_2$ | 48 | 0.464 | 0.010 | 1.169 | 0.2037 |
| Subject | 3 | 1.390 | 0.463 | 56.023 | <0.0001 |
| Frequency$\times$subject | 9 | 0.253 | 0.028 | 3.401 | 0.0004 |
| $\tau_1\times$subject | 12 | 1.435 | 0.120 | 14.455 | <0.0001 |
| $\tau_2\times$subject | 12 | 0.436 | 0.036 | 4.387 | <0.0001 |
| Frequency$\times\tau_1\times$subject | 36 | 1.377 | 0.038 | 4.625 | <0.0001 |
| Frequency$\times\tau_2\times$subject | 36 | 0.487 | 0.014 | 1.637 | 0.0109 |
| $\tau_1\times\tau_2\times$subject | 48 | 1.000 | 0.021 | 2.519 | <0.0001 |

results, pointer interaural delay showed a significant dependence on both $\tau_1$ and $\tau_2$ ($p<0.0001$). The fact that the interaction of frequency condition with each of these variables was also highly significant ($p<0.0001$) indicates that the differences between frequency conditions seen in Fig. 2 were significant as well.[1] If subject responses are left–right symmetric [so that $\alpha(\tau_1,\tau_2)=-\alpha(\tau_1,\tau_2)$], then there should be no effect of frequency condition or subject alone since the expected means averaged across all values of $(\tau_1,\tau_2)$ would be zero. Instead, the effect of subject was extremely significant ($p<0.0001$), while the effect of frequency condition reached marginal significance ($p<0.02$). Inspection showed that some subjects showed asymmetric responses in some frequency conditions. The extent and direction of these asymmetries depended upon both frequency condition and subject, thus explaining the significant interaction of these factors ($p<0.0005$). In addition, if $\mathbf{c}$ is independent of $(\tau_1,\tau_2)$, the interaction of $\tau_1$ with $\tau_2$ should not be significant. Instead, this interaction was highly significant ($p<0.0001$), indicating that $\mathbf{c}$ varied in a consistent way with $(\tau_1,\tau_2)$ across all other factors. Finally, all of the significant effects and interactions already mentioned also had a significant interaction with subject, except for the interaction (frequency condition$\times\tau_1\times$subject) which reached marginal significance ($p<0.02$), further emphasizing the existence of intersubject differences.

An additional ANOVA was performed which included the results for all six subjects, but which restricted the values of $(\tau_1,\tau_2)$ to those in the abbreviated stimulus set (all combinations of $-0.150$, 0, and 0.150 $\mu$s). These results are given in Table III. With this subset of data, many fewer factors cause significant effects, and results are roughly consistent with the model when assuming that $\mathbf{c}$ depends only on frequency condition (i.e., the factors $\tau_1$ and $\tau_2$ and the interactions of frequency condition with these terms were all significant at $p<0.0001$). The only other factors that reached significance were subject ($p<0.0005$) and the interaction of $\tau_1$ with subject ($p<0.001$), indicating some intersubject differences even for the restricted data set.

The individual-subjects' matrices of $\mathbf{c}$ values generated

TABLE III. Summary of multiway ANOVA results on $\alpha$ for equal-level, precedence-effect experiment with subject, frequency condition, $\tau_1$, and $\tau_2$ as factors, and including up to three-way interactions. Data for six subjects, with restricted range of $\tau_1$ and $\tau_2$ values.

| Factor | $df$ | Sum squares | Mean square | $F$ ratio | Prob. |
|---|---|---|---|---|---|
| Frequency | 3 | 0.002 | 0.001 | 0.294 | 0.830 |
| $\tau_1$ | 2 | 4.779 | 2.390 | 1078.400 | <0.0001 |
| $\tau_2$ | 2 | 0.446 | 0.223 | 100.680 | <0.0001 |
| Frequency$\times\tau_1$ | 6 | 0.203 | 0.034 | 15.271 | <0.0001 |
| Frequency$\times\tau_2$ | 6 | 0.189 | 0.032 | 14.250 | <0.0001 |
| $\tau_1\times\tau_2$ | 4 | 0.013 | 0.003 | 1.449 | 0.217 |
| Frequency$\times\tau_1\times\tau_2$ | 12 | 0.032 | 0.003 | 1.196 | 0.283 |
| Subject | 5 | 0.050 | 0.010 | 4.703 | 0.001 |
| Frequency$\times$subject | 15 | 0.028 | 0.002 | 0.841 | 0.631 |
| $\tau_1\times$subject | 10 | 0.071 | 0.007 | 3.196 | 0.001 |
| $\tau_2\times$subject | 10 | 0.022 | 0.002 | 0.985 | 0.456 |
| Frequency$\times\tau_1\times$subject | 30 | 0.082 | 0.003 | 1.239 | 0.183 |
| Frequency$\times\tau_2\times$subject | 30 | 0.060 | 0.002 | 0.900 | 0.622 |
| $\tau_1\times\tau_2\times$subject | 20 | 0.039 | 0.002 | 0.881 | 0.612 |

by combinations of $(\tau_1,\tau_2)$ were inspected for systematic dependencies. The results of Shinn-Cunningham *et al.* (1993) using wideband noise bursts suggested a relatively simple dependence of **c** on $\tau_1-\tau_2$ for a lag of 10 ms; for a lag of 1 ms, the precedence effect was nearly complete in all cases and **c** was near one for all $(\tau_1,\tau_2)$. The current results showed no consistent, systematic effects depending on $(\tau_1,\tau_2)$. However, for a given frequency condition and subject, the values of **c** did vary quite substantially for different combinations of $(\tau_1,\tau_2)$ compared to the variability in subject's responses. Thus while the choice of $(\tau_1,\tau_2)$ caused significant changes in performance for a given subject, there were no clear or simple trends which were consistent across subjects. Consistent with the ANOVA of match responses, strong asymmetries were evident for some subjects in some conditions.

The above results demonstrate that many factors cause consistent changes in performance, but that most of these changes are insignificant when the range of $\tau_1,\tau_2$ values is restricted. Since much of the variability in the results (even with the larger range of $\tau_1,\tau_2$) can be accounted for in regression analysis using $\tau_1$ and $\tau_2$ as variables, the overall sizes of the effects of other factors must be relatively small even though they are highly statistically significant. The main effect of interest in the current study is how frequency content affects the relative localization strength of the bursts. Thus in this study we focus on how estimates of **c** (a measure of the relative localization strengths of the bursts) depend upon frequency condition, ignoring the small, albeit significant effects of $\tau_1$ and $\tau_2$ on **c**.

Separate one-way ANOVAs were performed on the values of **c** (found for each $\tau_1,\tau_2$ pair in which $\tau_1 \neq \tau_2$) to compare all possible pairs of frequency conditions. First, the conditions H–H and L–H were compared in one ANOVA and were found to be statistically indistinguishable ($p=0.58$). All other possible combinations of frequency conditions were significantly different from each other ($p<0.0001$). A subsequent two-way ANOVA on **c** in which the H–H and L–H conditions treated as a single condition was then performed. As predicted from ANOVA analysis of the raw match data, frequency condition, subject, and their interaction were all highly significant ($p<0.0001$). The average of **c** across subject, $\tau_1$, and $\tau_2$ was 0.89 for the combined L–H, H–H condition and was 0.77 and 0.49 for the L–L and H–L conditions, respectively.

Of most interest in the current study is the simple frequency effect wherein the H–H stimulus results in a stronger precedence effect than does the L–L stimulus. In addition, there is a large asymmetry across frequency, such that the L–H stimulus produces a much stronger precedence effect than does the H–L stimulus. These results are seen graphically in Fig. 3, where values of **c** were averaged across $(\tau_1,\tau_2)$ combinations for each subject and each condition (to yield $\mathbf{c}_{ave}$) and plotted for the four combinations of L and H noise bands in the leading and lagging positions. For subjects RC, JG, SN, and DL, $\mathbf{c}_{ave}$ is an average of the 60 **c** values for which $\tau_1 \neq \tau_2$. For subjects PZ and BGSC, $\mathbf{c}_{ave}$ is an average of 12 values of **c**. For comparison, results are also shown from Shinn-Cunningham *et al.* (1993) in which identical leading and lagging wideband noise bursts were presented at

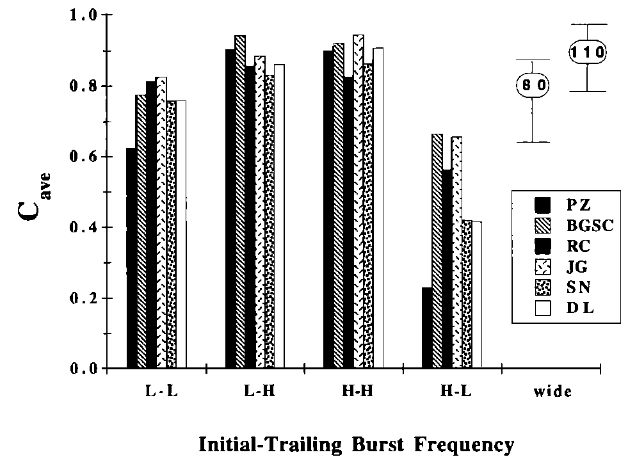


FIG. 3. Values of $c$ for the four stimulus frequency conditions. Each bar gives the average $c$ computed across multiple runs for each of six subjects. The values plotted for wideband stimuli on the far right are taken from the results of Shinn-Cunningham *et al.* (1993), and correspond to the average values of $c$ for 80 and 110 dB SPL white-noise bursts.

two different levels (80 and 110 dB SPL). The strength of the precedence effect in the earlier study is roughly comparable with present results. The direction of the cross-frequency asymmetry seen in Fig. 3 is the same as that described by Blauert and Divenyi (1988) and Divenyi (1992).

## III. EXPERIMENT 2: SIMULTANEOUS BURSTS WITH VARIED LEVELS

### A. Methods

The results of the first experiment confound two possible factors which could affect lateralization: a simple spectral effect whereby low-frequency stimuli carry more perceptual weight than do high-frequency stimuli and a temporal effect whereby leading sources carry more weight than do lagging sources. In order to separate any spectral dominance effects from temporal (precedence) effects, we removed the temporal factor and measured the remaining low-frequency dominance. To this end, subjects matched the lateral position of test stimuli in which low and high bursts were presented simultaneously [i.e., the lag was zero as shown in Fig. 1(b)]. A recent paper (Aoki and Houtgast, 1992) showed that both lateralization and diffuseness of a sound image comprised of two bursts shows a precedence effect, and that the relative influence of a burst can be increased by increasing the relative intensity or duration of the burst. In the current experiment, the ratio of the levels of the high- and low-frequency bursts was parametrically varied in order to find relative levels at which the two bursts were equally influential on the lateral position of the test stimulus.

Since bursts were simultaneous, only one frequency condition was tested: that in which one L burst and one H burst were presented. Six different level conditions were tested, with the level of the low-frequency burst set to either 0, 3, 6, 9, 12, or 15 dB below the level of the high-frequency burst. The high-frequency burst level was always scaled to an rms of 87 dB SPL. Each run consisted of nine matches

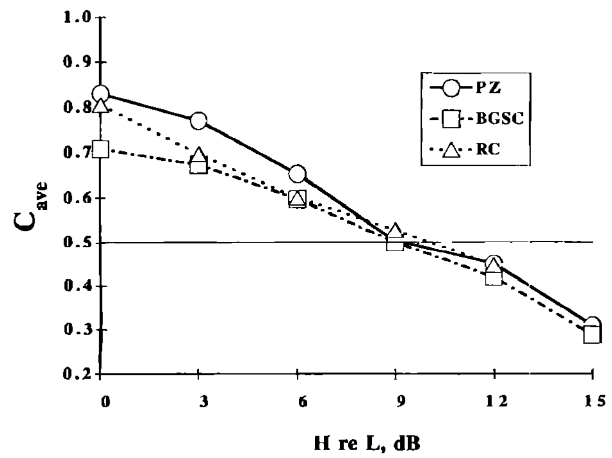


FIG. 4. Values of $c$ with L–H stimuli and zero lag, as a function of the intensity ratio between high and low noise bursts. Data for three subjects.

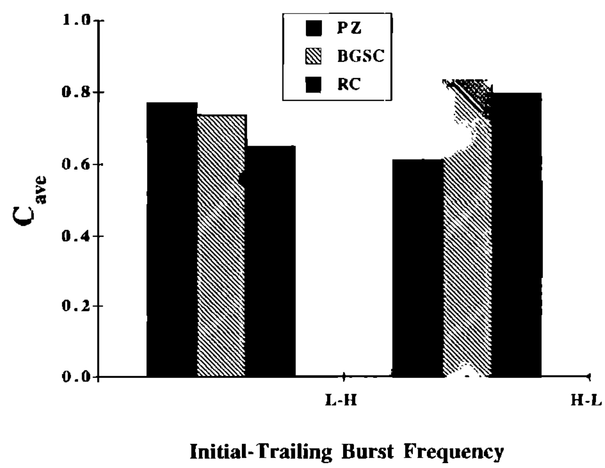


FIG. 5. Values of $c$ for L–H and H–L stimuli with a 1-ms lag when bursts are level compensated. Data for three subjects. The intensity ratios between low and high components were chosen individually for each subject to result in $c$=0.5 with zero lag.

using the abbreviated ($\tau_1,\tau_2$) stimulus set and every condition replicated twice by each of subjects RC, PZ, and BGSC in random order.

### B. Results

The results of the level variation are shown in Fig. 4 where the value of **c** averaged across ($\tau_1,\tau_2$) is plotted as a function of the intensity ratio (L/H) of the bursts for each subject. For purposes of computing **c**, the low-frequency burst was associated with $\tau_1$ in Eq. (1); thus values of **c** greater than 0.5 indicate greater contribution from the low-frequency burst. The dominance of the low-frequency burst is evidenced by values of $\mathbf{c}_{\text{ave}}$ between 0.72 and 0.82 for the three subjects when L and H have equal levels. As the intensity ratio of H to L bursts was increased, $\mathbf{c}_{\text{ave}}$ declined.

For each subject, the relative level at which the simultaneous L and H bursts were equally influential on the lateral position of the test stimulus was estimated as the level for which $\mathbf{c}_{\text{ave}}$ was equal to 0.5. This level was found by linearly interpolating $\mathbf{c}_{\text{ave}}$ for the conditions tested. Critical intensity ratios, where $\mathbf{c}_{\text{ave}}=0.5$, were estimated to be 9 dB for PZ and BGSC and 10 dB for RC.

## IV. EXPERIMENT 3: SEQUENTIAL BURSTS WITH COMPENSATED LEVELS

### A. Methods

In the final experiment, lag was once again set to 1 ms and further pointer adjustments made. The same three subjects (RC, PZ, and BGSC) were tested with stimuli in which the ratio of low-to-high-frequency burst level was set to the critical level found for each subject in the previous experiment. Thus precedence-effect stimuli were constructed that used burst level to compensate for low-frequency dominance in lateralization judgements. Two conditions (L–H and H–L) were tested using the abbreviated stimulus set, and two replications were performed for each condition.

### B. Results

A multiway ANOVA analysis of the raw match results (with factors of frequency condition, $\tau_1,\tau_2$, and subject, and including up to three-way interactions) showed that $\tau_1$ and $\tau_2$ were both significant factors ($p<0.0001$). Subject differences were also significant ($p<0.005$), while the interaction of subject and $\tau_1$ reached marginal significance ($p<0.02$). No other factors were significant. These results are consistent with the hypothesis that the level-compensated L–H and H–L conditions are equivalent.

In an ANOVA analysis of **c** values, neither frequency condition nor subject was significant, although their interaction reached marginal significance. *Post hoc* analysis revealed that only the difference between subject PZ and subject BGSC in the H–L condition was marginally significant ($p<0.02$). Summary results can be seen in Fig. 5, which plots the average value of **c** for each subject and condition. As suggested by the ANOVA, this figure indicates a residual precedence effect that is, on average, nearly equal for the L–H and H–L stimuli ($\mathbf{c}_{\text{bar}}=0.72$ and 0.74, respectively). Thus there is still a precedence effect that operates across frequency—and to a statistically equal extent in both directions—once the inherent dominance of L over H stimuli is removed.

## V. DISCUSSION

The strength of the precedence effect found with the present narrow-band stimuli is roughly comparable to that found using wideband stimuli in the study by Shinn-Cunningham *et al.* (1993 . One notable difference between the results was that the parameter **c** depended systematically on the difference between $\tau_1$ and $\tau_2$ in the earlier study. The systematic variation found in this earlier study only became apparent at a lag of 10 ms, when the precedence effect was weak. In the current study, the precedence effect was weak when equal-level bursts were used in the H–L condition with a 1-ms lag; however, values of **c** did not show the same consistent dependence on the difference $\tau_1-\tau_2$. A number of experimental differences may account for the difference in results. Most obviously, it may be that the cross-spectral precedence effect does not show systematic variations in strength with $\tau_1$ and $\tau_2$. A second possibility is that these patterns do not necessarily arise when the precedence effect is weak, but rather when the lag is relatively long. In the current study, a 1-ms lag was used in all conditions, and the relative weakness of the precedence effect in the H–L condition arises from the inherently different localization strengths of low and high bursts, while in the earlier study the precedence effect was weak because the lag was long.

The present results are consistent with those of Blauert and Divenyi (1988) and Divenyi (1992) in showing a larger precedence effect with a low-frequency burst leading a high-frequency equal-level burst. Two differences between studies need to be noted, however, and the first concerns measurement methods. Blauert and Divenyi (1988) and Divenyi (1992) employed a discrimination paradigm in which the precedence effect was assessed by the degree to which a brief leading diotic sound interfered with interaural-delay resolution for the trailing sound. The comparability of discrimination results to lateral position measurements was recently demonstrated by Shinn-Cunningham *et al.* (1993). They found that the two types of measures can be simply related when the two component sounds are fused into a single image (so that lateral position measurements can be performed without confusion). Thus we feel confident in comparing results across studies using these two different methods.

The second difference concerns the nature of the interaural delay cues present in the stimuli. The stimuli in the present study were confined to the frequency range below 1500 Hz where the dominant interaural-delay cue is carried by the fine structure (carrier) of the waveforms. The stimuli used by Blauert and Divenyi (1988) and Divenyi (1992), on the other hand, either straddled the 1500-Hz border between low-frequency, fine-structure coding and high-frequency envelope-delay coding, or were confined to the high-frequency range. The effects of these stimulus differences on the outcome of these studies, however, are not yet clear.

In discussing their finding of a spectrally asymmetric precedence effect, Blauert and Divenyi (1988) and Divenyi (1992) considered and dismissed the possibility that it might arise from a direct upward-spread-of-masking that would diminish the contribution of the higher-frequency component. Rather, Blauert and Divenyi (1988) suggested a localization masking effect that would also be asymmetric in frequency like traditional monaural spread of masking. Divenyi (1992) revised this notion to involve the localization strength of the leading and lagging components.

In the present study the notion of unequal localization strength was put to the test by showing that there was such an inequality when the low- and high-frequency components were simultaneous. Then, this imbalance was equalized through relative intensity adjustment, using overall burst intensity to alter the relative salience of interaural time delay of the burst (similar to a study by Aoki and Houtgast, 1992). With this equalization, the precedence effect was roughly equal for L–H and H–L stimuli. Assuming the generality of this result, which was demonstrated here with an admittedly limited set of data (using only one interburst delay, interaural timing differences alone, only one pair of stimulus frequencies, and only three subjects), it indicates that the spectral asymmetry of the precedence effect seen with equal-level components is the result of the localization strength of the components, while the precedence effect itself is equally strong both upward and downward in frequency.

It is interesting that the size of the precedence effect ($\mathbf{c} \approx 0.72$) in the level-equalized conditions is about the same as measured in the L–L condition, indicating little diminution of effect on the trailing L component by moving the leading component from the L region (300–600 Hz) to the H region (1100–1400 Hz). The fact that the precedence effect in the H–H condition is substantially stronger than in the L–L condition complicates a simple interpretation, however. Previous results on the simple effect of bandpass center frequency (same filtering for both leading and lagging sounds) are not entirely consistent. Blauert and Divenyi (1988) found unmeasurably large precedence effects (interference with resolution of second-burst interaural delay) at bandpass center frequencies of 0.5, 1.5, and 4.5 kHz. Divenyi (1992), on the other hand, found little or no precedence effect at a center frequency of 2.0 kHz, and suggested that differences in the correlation between first- and second-burst tokens may be responsible for the different results between the two studies. Because of this uncertainty and the present indication that the precedence effect with bandpass stimuli might depend heavily on center frequency, we plan to study this topic further.

Our own interpretation of the present results is similar to that suggested by Divenyi (1992), but we suggest an economization on terms. The notion of spectral dominance in sound lateralization has existed at least since Bilsen and Raatgever's (1973) brief demonstration. That study and later ones in which interaural-delay cues are placed in conflict across frequency (Zurek, 1985; Trahiotis and Bernstein, 1990; Wightman and Kistler, 1992) indicate that lateralization and localization (when the sound image is still unitary) is more strongly influenced by low-frequency timing cues, particularly those around 700 Hz. We feel that this phenomenon is also at work in the studies of Blauert and Divenyi (1988) and Divenyi (1992). Until distinguishing features are identified, we take localization masking (Blauert and Divenyi, 1988), localization strength (Divenyi, 1992), and "spectral dominance" to be equivalent terms. On the other hand, we reserve the term "precedence effect" to refer to temporal order effects that remain once spectral dominance has been factored out.

The present results contribute to the development of models of complex sound lateralization and the precedence effect. In particular, the finding of a precedence effect with stimuli separated by over an octave that is as large as that obtained with stimuli within the same band suggests that the effect is probably not occurring at peripheral levels where spectral selectivity is still in force. Rather, a simpler picture, and one consistent with other evidence (Zurek, 1987; Rakerd and Hartmann, 1992) is that the precedence effect is a relatively central phenomenon acting on auditory images formed after spectral assimilation.

In summary, the present results suggest that the precedence effect operates across spectral regions with about the same strength as when leading and lagging bursts are within the same spectral band. The effect does not seem to be asymmetric with frequency once the inherent dominance of low-frequency interaural delay is factored out. However, further work is needed to (1) investigate the subject differences seen in the current results, (2) explore whether similar results are found for stimuli with localization and lateralization cues other than simple interaural delays, and (3) confirm the current findings for other combinations of stimulus frequencies and temporal parameters.

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[1] A multiway ANOVA which included only the L–H and H–H frequency conditions found no statistically significant effects due to frequency condition or to any interaction of frequency condition with other factors, demonstrating that the similarity of the two conditions seen in Fig. 2 holds across subjects as well. The similarities of these two conditions may be due in part to the strength of the precedence effect in these cases; although there are systematic changes in mean position with $\tau_2$, these changes are quite small and $\alpha$ is nearly equal to $\tau_1$ for all subjects and values of $\tau_1$ and $\tau_2$.

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