Investigation of the relationship among three common measures of precedence: Fusion, localization dominance, and discrimination suppression

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Listeners have a remarkable ability to localize and identify sound sources in reverberant environments. The term ''precedence effect'' (PE; also known as the ''Haas effect,'' ''law of the first wavefront,'' and ''echo suppression'') refers to a group of auditory phenomena that is thought to be related to this ability. Traditionally, three measures have been used to quantify the PE: (1) *Fusion*: at short delays (1–5 ms for clicks) the lead and lag perceptually fuse into one auditory event; (2) *Localization dominance*: the perceived location of the leading source dominates that of the lagging source; and (3) *Discrimination suppression*: at short delays, changes in the location or interaural parameters of the lag are difficult to discriminate compared with changes in characteristics of the lead. Little is known about the relation among these aspects of the PE, since they are rarely studied in the same listeners. In the present study, extensive measurements of these phenomena were made for six normal-hearing listeners using 1-ms noise bursts. The results suggest that, for clicks, fusion lasts 1–5 ms; by 5 ms most listeners hear two sounds on a majority of trials. However, localization dominance and discrimination suppression remain potent for delays of 10 ms or longer. Results are consistent with a simple model in which information from the lead and lag interacts perceptually and in which the strength of this interaction decreases with spatiotemporal separation of the lead and lag. At short delays, lead and lag both contribute to spatial perception, but the lead dominates (to the extent that only one position is ever heard). At the longest delays tested, two distinct sounds are perceived (as measured in a fusion task), but they are not always heard at independent spatial locations (as measured in a localization dominance task). These results suggest that directional cues from the lag are not necessarily salient for all conditions in which the lag is subjectively heard as a separate event.
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I. INTRODUCTION

When a sound is produced in a reverberant environment, it propagates in multiple directions and is subsequently reflected from various surfaces. The complex array of stimuli received by the listener consists of multiple sounds, each of which carries its own set of localization cues. In order to avoid localization errors, the auditory system must resolve which cues belong to the source and assign greater weight to them in the localization process. Efforts to understand how the auditory system processes sounds in complex environments have utilized simple stimulus paradigms in which a source (lead) and a single simulated reflection (lag) are presented in anechoic environments with short delays (1–5 ms for clicks, 30–50 ms for speech and music) between their onsets. Many studies have shown that the localization information in the source receives greater perceptual weight than, or has *precedence* over, the reflections; hence, this phenomenon is commonly known as the precedence effect (Cremer, 1948; Wallach *et al.*, 1949; Zurek, 1980; Blauert, 1997; Litovsky *et al.*, 1999).

Several perceptual phenomena related to the precedence effect have been quantified over the years. *Fusion* refers to the finding that at short delays listeners hear one fused auditory event, but fusion breaks apart as delays are increased (e.g., Blauert, 1997; Freyman *et al.*, 1991). *Discrimination suppression* refers to the general finding that a listener's ability to detect changes in directional cues in the lag is poor compared to sensitivity to changes in the lead (e.g., Zurek, 1980; Shinn-Cunningham *et al.*, 1993; Tollin and Henning, 1998). *Localization dominance* refers to the finding that the perceived location of a fused sound is dominated by the directional information in the lead (e.g., Wallach *et al.*, 1949; Zurek, 1980; Blauert and Divenyi, 1988; Divenyi, 1992; Shinn-Cunningham *et al.*, 1993; Litovsky *et al.*, 1997).

Studies of fusion date back to the early part of the century (cf. reviews by Blauert, 1997; Litovsky *et al.*, 1999). A common experimental paradigm presents numerous trials

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with the lead–lag delay randomized; the listener reports her subjective impression of whether one or two sounds are heard on each trial. For click stimuli, at short delays (1–5 ms) most listeners report hearing only one sound on 100% of trials; at long delays (8–10 ms) most listeners report hearing two sounds on 100% of trials; at intermediate delays there is a transition in the percentage of trials in which ''two sounds'' are reported. In general, the percentage of ''two sound'' trials increases fairly steeply with delay, although the exact delay at which this sharp transition occurs varies across individuals (e.g., Freyman *et al.*, 1991). This critical delay, known as the *echo threshold*, is usually defined as the delay at which two sounds are reported on some predetermined percentage of trials (usually between 50% and 75%). Echo threshold varies with stimulus conditions, testing situation, and instructions given to the listener (Zurek, 1987; Blauert, 1997). Finally, it should be noted that the fusion task does not measure masking; listeners can detect the presence of the lag even when they do not perceive the lag as a separate auditory event.

Most localization dominance studies have been conducted under headphones using ''adjustment'' protocols. In these experiments, listeners match the position of a reference stimulus by setting interaural parameters (such as time, ITD, or level, ILD) of a test stimulus. This approach provides a quantitative measure of the relative influence of lead and lag binaural cues on lateralization (von Bekesy, 1960; Wallach *et al.*, 1949; Haas, 1951, 1972; Snow, 1954; Leakey and Cherry, 1957; Yost and Soderquist, 1984; Shinn-Cunningham *et al.*, 1993). These studies show that when the delay is a few milliseconds, the heard location of a fused image is much nearer to the position of the lead (presented in isolation) than that of the lag. Localization cues of the lag also contribute to the lateralization; however, when the delay is near or equal to zero, the perceptual influence of the lag increases until it contributes almost equally to the overall spatial impression. Although free-field measurements of localization dominance are less common, these studies also show that the lag contributes relatively little to the perceived location of the fused image (Hafter *et al.*, 1992; Litovsky *et al.*, 1997).

Studies of discrimination suppression have been conducted under headphones by measuring the just-noticeable-difference (jnd) in the ITD (e.g., Zurek, 1980; Shinn-Cunningham *et al.*, 1993; Saberi and Perrott, 1990) or ILD (Zurek, 1980; Gaskell, 1983) of the lagging source. In free field, measurements have been made for discrimination of the azimuthal direction of the lagging source (Perrott *et al.*, 1989; Freyman *et al.*, 1991; Litovsky and Macmillan, 1994; Yang and Grantham, 1997a, 1997b; Litovsky, 1997). At short lag delays, changes in the lag location (or binaural disparities) are difficult to discriminate relative to comparable differences in the lead. As the delay increases, lag discrimination performance improves dramatically, presumably because directional information in the lag becomes more salient.

Historically, the three aforementioned psychophysical measures have all been attributed to a single phenomenon, namely, the precedence effect. However, the relation among them is not well understood, in part because measures on all three tasks have never been obtained in the same listeners. Although it is often assumed that all measures reflect the fact that information in the lag is rendered perceptually inaccessible (e.g., Zurek, 1980; Freyman *et al.*, 1991), few studies have included parallel measurements of lag discrimination and either fusion or localization dominance. Comparisons that have been made do not uniformly agree. For instance, fusion and discrimination suppression are thought to reflect similar processes when single pairs of lead–lag stimuli are used (Freyman *et al.*, 1991), but not when a train of lead–lag stimuli is presented and the ''buildup of echo suppression'' occurs (Yang and Grantham, 1997a). Does the lag have to be perceived as a separate event from the lead in order for lead and lag discrimination to be equivalent? Can directional information of the lag be accessed even when the lag is still fused with the lead? While it has been suggested that localization dominance and discrimination suppression reflect similar processes (Shinn-Cunningham *et al.*, 1993), the relation of fusion and localization dominance has never been explored.

This study has two main purposes. The first is to quantify localization dominance in conditions for which two distinct sources may be perceived. Previous studies have either not allowed for responses that measure more than one source position (Shinn-Cunningham *et al.*, 1993) or have confounded temporal order confusion with localization dominance (Stellmack *et al.*, 1999). The second purpose is to directly compare fusion, discrimination suppression, and localization dominance measures in the same listeners, using similar stimuli. By directly comparing the delays at which listeners recover from ''precedence,'' as defined by each measure, we can begin to address whether a single computational mechanism underlies these three phenomena.

In order to relate the current results to previous reports, experimental procedures used in the current study are based on those commonly used in earlier experiments. Thus, whereas the discrimination suppression experiment uses an objective measure, the fusion experiment asks subjects to report their subjective impression of how many events are heard (an approach that confounds subject criteria with differences in sensitivity). In addition, the number of intervals in a trial differed across the three experiments, even though the basic stimuli were otherwise comparable. To the extent that precedence build-up may have influenced results, differences across the three experiments may be partially explained by a difference in build-up. However, despite these cautionary notes, the results reported herein are the first that allow direct within-subject comparisons of performance on all three precedence measures.

II. METHODS

A. Subjects

Six adults (two male, four female) participated as subjects in all experiments. All had pure-tone thresholds of 15 dB HL or less at octave frequencies between 250 and 8000 Hz. The ages of the listeners ranged from 19–22 years. Two

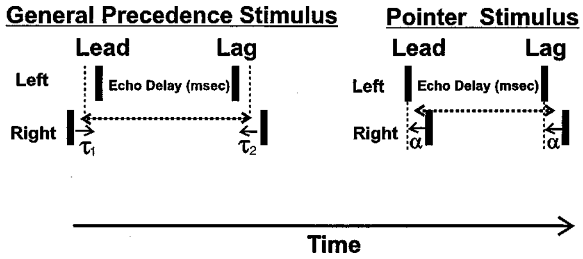

FIG. 1. General precedence stimulus (left) used for all three experiments and pointer stimulus (right) used on the localization dominance pointer task. Stimuli consisted of 1-ms Gaussian noise bursts with a 0-ms rise–decay time. The lead and lag each consisted of a pair of binaural noise bursts presented with a specified interaural time differences (ITDs), denoted as τ_1 for the lead and τ_2 for the lag. The echo delay represents the delay between the lead and lag pairs, defined as the time interval between the midpoints of τ_1 and τ_2. In the general stimulus, τ_1 and τ_2 could have ITD values that were either the same or different. In the pointer stimulus, the lead and lag pairs had the same ITD value.

listeners had previous experience in psychoacoustic tasks (S4, S5). All listeners were given a minimum of 1 h of practice on each of the tasks.

All testing was conducted in a double-walled soundproof booth. Testing was initially conducted on the fusion task, was followed by a randomized sequence of trial blocks for the discrimination and pointer tasks, and ended with a repetition of the fusion measurements.

B. Stimuli

A Tucker-Davis Technologies System II stereo analog interface was used to construct the stimuli. The output was fed through a 16-bit DAC to Sennheiser HD 520 II headphones. The general precedence stimulus (Fig. 1) was used for all three experiments. All stimuli consisted of 1-ms Gaussian noise bursts with a 0-ms rise–decay time. A lead–lag stimulus configuration consisted of two pairs of binaural noise bursts presented with various combinations of interaural time differences (ITDs) for the lead (τ_1) and lag (τ_2) pairs. Within a given interval, lead and lag were identical noise samples with new samples chosen for each interval. Delays varied from 1–15 ms.

C. Test parameters

1. Fusion

On each trial, the general stimulus was presented three times, with interstimulus intervals of 500 ms. The ITDs of the lead and lag were constant within each trial. ITDs for lead and lag were chosen from the set (+400, 0, −400) μs, for a total of nine combinations. For five of the six subjects, eight delays were used (1, 2, 3, 5, 7, 10, 12, and 15 ms). The sixth subject was also tested at longer delays of 20, 30, 50, 70, and 100 ms (see Sec. III). On each trial, the ITDs and delays were randomly chosen. A total of 20 trials were presented at each delay and lead/lag ITD combination for a total of 1440 trials per listener. On each trial, listeners were instructed to report whether they perceived ''one fused auditory event'' or ''two sounds'' on the third interval. Listeners were aware of the fact that two events were always present in each interval. No feedback was provided, since two stimuli were always present. Testing was repeated both prior to (first run) and following (second run) all other experiments.

2. Discrimination suppression

On each trial, the general stimulus was presented three times in an ABX forced-choice task. In this procedure, the ''target'' ITD of the first (A) and second (B) interval differed. The target ITD of the third interval (X) was randomly chosen to equal either that of A or B with equal likelihood. The nontarget ITD and the lead/lag delay were the same in all three intervals of a given trial. Three conditions were tested that differed in the ''target'' ITD. In one condition, the target was the ITD of the lead in the general precedence stimulus (Fig. 1). In the second condition, the target was the lag ITD. The final condition was a control in which only one binaural burst was presented (i.e., the control did not use a precedence stimulus).

An adaptive procedure was used to estimate the jnd in the target ITD at different reference ITDs and delays. In each run, the delay and reference ITD were fixed. The change in the target ITD (around the reference) varied adaptively using a modified 2-down/1-up protocol with 14 reversals (Hawley, 1994). The starting ITD was 400 μs. For the first four reversals the ITD was either increased or decreased by a factor of 2; subsequent changes were by a factor of 1.4. Threshold was estimated by averaging the ITDs of the last ten reversals. Feedback was provided on every trial. Thresholds were obtained at delays of 1, 2, 3, 5, 10, and 15 ms for the two conditions (lead- and lag discrimination) using the general precedence stimulus. The reference target ITD was either 0 (center) or −400 μs (left). In each trial of lead- and lag discrimination, the ITD of the noise burst that was not being discriminated (lag and lead, respectively) was chosen randomly (from a uniform distribution ranging from −500 to 500 μs), forcing listeners to use directional information in the target to perform the task. All delay and stimulus combinations were repeated three times with the order of the conditions randomized.

3. Localization dominance

In the final task, listeners adjusted an acoustic pointer to indicate lateral positions of a target stimulus. On each trial, listeners alternated between listening to the general stimulus (target) and the pointer stimulus (Fig. 1). The pointer stimulus had the same basic structure and temporal characteristics as the general stimulus, except that the lead and lag ITDs were equal. Listeners controlled the ITDs of the pointer by adjusting a potentiometer dial. ITDs could vary between $\pm$1000 μs in steps of 10 μs. Subjects were asked to indicate the perceived location(s) of the lead/lag target by adjusting the pointer ITDs. Since two images are often perceived at the longer delays used in the experiment, measurements were repeated twice for all stimuli, with two separate sets of instructions. On half of the trials listeners were told to match the ''right-most'' image; on half of the trials instructions were to match the ''left-most'' image. If only one image was heard, both instructions should yield identical results. The right-most and left-most trial types remained constant within a block, and the order of the blocks was randomized within each session. The final ITD of the pointer (the subject response) will henceforth be referred to as ''alpha'' or the ''matched ITD.''

Stimuli alternated between seven presentations of the target and nine presentations of the pointer. The pointer location could be adjusted while it was being presented. Stimuli automatically alternated between target and pointer until the listener indicated confidence in their match by pressing a button. The ITDs of the lead and lag (τ_1 and τ_2), and the delay (1, 2, 3, 5, 10, and 15 ms) varied from trial to trial, but were held constant within each trial. ITDs of both lead and lag were chosen from the set $\{+400, 0, -400\ \mu s\}$ for a total of nine combinations. Each condition was repeated five times for every listener. Presentation order of all ITD combinations and delays was randomized, and testing was conducted in blocks lasting approximately 1.5 h.

III. RESULTS

A. Fusion

Data from all six listeners are shown in Fig. 2. For S1–S5, the first and second measurements (left and right panels, respectively) are shown (S6 is discussed in more detail below). The percentage of trials on which listeners reported two sounds is plotted as a function of delay; dashed horizontal lines indicate 70.7% (echo threshold as proposed by Yang and Grantham, 1997a). Data from conditions with the same absolute difference between ITDs of lead and lag are averaged, and each plot compares data for differences of magnitude 0, 400, and 800 μs.

For all subjects, fusion was strongest at short delays, where the proportion of two sounds reported was very low. As delay increased, fusion broke down and two sounds were heard on a majority of trials. Three aspects of the data are noteworthy. First, echo threshold delay varied dramatically across listeners (see Table I). For example, in the first run, some listeners reached echo threshold at delays equal to or less than 5 ms for the majority of conditions (S2, S3, S5). Echo thresholds were slightly higher for S1 (4.7–6.5 ms) and even larger for S4 (8.7–12 ms). One listener (S6) needed extraordinarily long delays (on the order of tens of milliseconds) to recover from fusion. For this subject, additional delays were tested after the initial results had been gathered on all three tasks. Results using these longer delays are shown in the bottom-most right panel. For this subject, echo thresholds were around 45 ms.

A second interesting aspect to note is that fusion results changed for some subjects between the first and second fusion sessions (measured before and after the discrimination and localization data were gathered). For S2, S4, and S5, there was a tendency for fusion to increase during the second session compared to the first session. The echo thresholds for S3 did not seem to change. Echo thresholds for S1 showed small decreases between the first and second sessions. For S3 and S6, there was no clear effect of experience on echo threshold.

Finally, we examined the effect of spatial separation between lead and lag. In Fig. 2, results are combined across

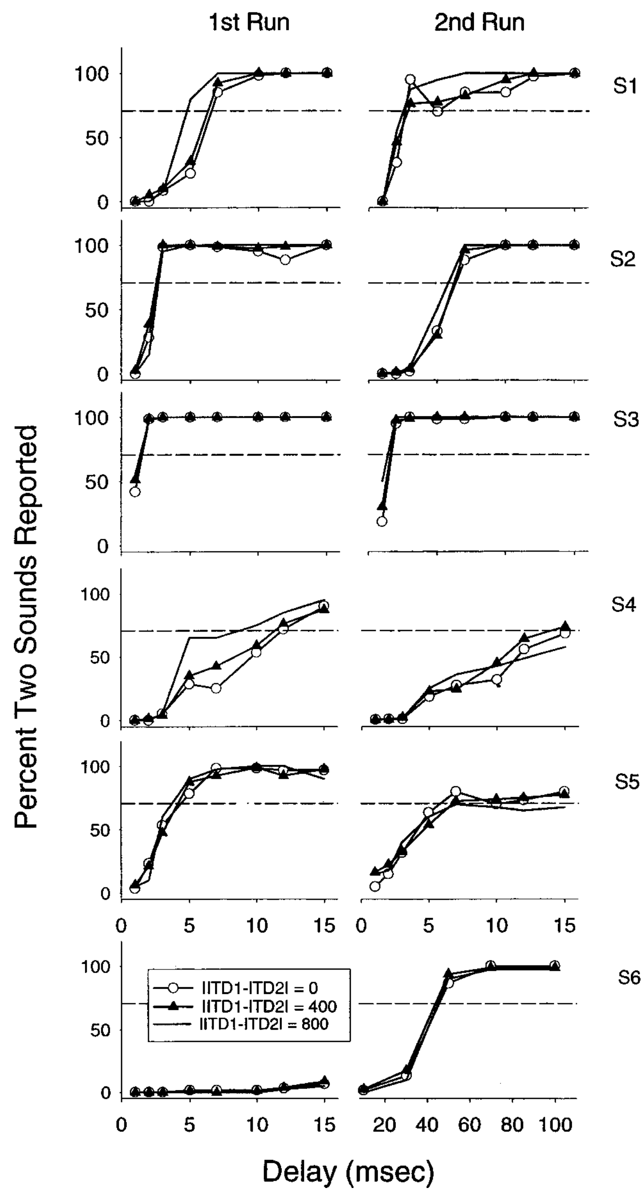

FIG. 2. Fusion results are shown for the six listeners tested. Left and right columns show data collected before and after the discrimination and pointer data, respectively. Each plot shows the percentage of trials on which the subjects reported hearing two sound images as a function of the lead–lag delay. For five subjects (S1–S5) delays ranged from 1–15 ms. For S6 the left column shows data at 1–15 ms, and the right column shows results from further testing conducted at longer delays. Within each plot the different lines show data collapsed according to the absolute value of the difference between the lead and lag ITDs.

conditions in which the spatial separation was either 0 μs (lead and lag at same location), 400 μs (lead at 0 and lag at $\pm$400, or vice versa), and 800 μs (lead at +400 and lag at $-$400, or vice versa). There was no consistent influence of lead/lag ITD on echo threshold in the fusion data measured in the current study.

B. Discrimination suppression

Data for the six listeners are shown in Fig. 3. Interaural-time difference (ITD) jnd's are plotted as a function of delay for lead (filled symbols) and lag discrimination (open symbols). Each data point in Fig. 3 represents the overall mean

TABLE I. Mean echo thresholds (for six subjects) for conditions in which the absolute difference between lead–lag ITDs were either 0, 400, or 800 μs. Thresholds are shown for the first and second measurements obtained before and after testing discrimination and pointer tasks, respectively.

	First run			Second run		
Subject	$\|\tau_1-\tau_2\|=0$	$\|\tau_1-\tau_2\|=400$	$\|\tau_1-\tau_2\|=800$	$\|\tau_1-\tau_2\|=0$	$\|\tau_1-\tau_2\|=400$	$\|\tau_1-\tau_2\|=800$
1	6.7	6.3	4.7	2.6	2.9	2.7
2	2.6	2.5	2.7	6.4	6.2	5.8
3	1.5	1.4	1.4	1.7	1.6	1.4
4	11.9	11.4	8.7	>15	14	>15
5	4.4	4.1	3.7	5.9	6.8	7.0
6	N/A	N/A	N/A	45.6	44.0	45.2

for the conditions at each delay. Error bars show the standard error around the means across six repetitions (three per condition). Performance depended strongly on delay for five of the six listeners and weakly for S6 (the remaining subject). At short delays lag discrimination was poor, evidenced by large ITD jnd's. In contrast, lead discrimination performance was relatively good at the short delays, as evidenced by much smaller ITD jnd's. Analyses of variance tests examining the effect of the two reference conditions (0 μs and -400 μs) found no significant difference between the conditions ($p>0.05$), as expected from the results shown in Fig. 3.

The results show that at short delays, listeners were able to use directional information in the lead much more readily than directional information in the lag. This presumably reflects the fact that for precedence effect conditions, the lead carried more perceptual weight in localization than the lag (e.g., Zurek, 1980; Shinn-Cunningham *et al.*, 1993). As delays increased, lag discrimination improved so that by 10 ms, lead and lag performance was roughly equal. This result suggests that precedence was no longer effective by 10 ms. For some listeners (S1, S3, S5), lead discrimination was actually worse than lag discrimination at delays greater than 10 ms. This reversal suggests that at these long delays (and for these subjects), the lag interfered with the lead ITD information more than the lead interfered with the lag ITD information. Finally, intersubject differences were large. For instance, the difference between lead and lag conditions was greater for three listeners (S1, S2, S3), primarily due to better lead discrimination at the shortest delays. In contrast, results for S6 suggest that lead and lag interact strongly at all delays, as evidenced by poor discrimination in both the lead and lag conditions for all measured delays.

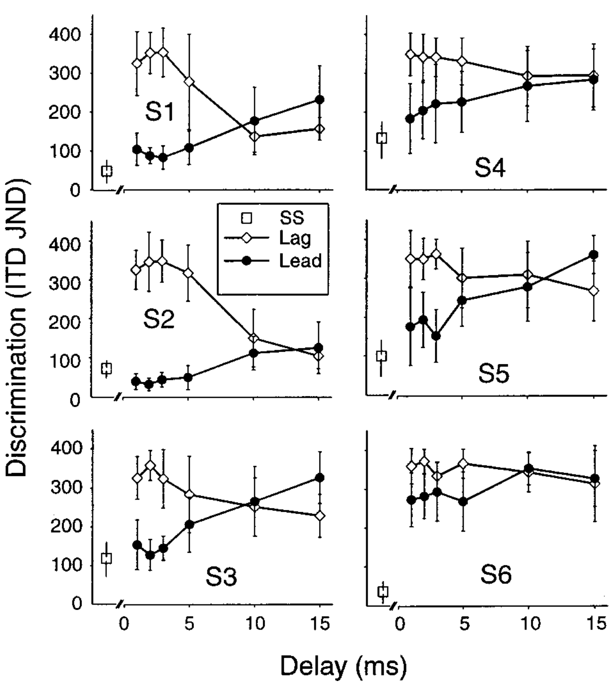

FIG. 3. Discrimination results are shown for the six listeners tested. ITD jnd's are plotted as a function of delay for lag (open symbols) and lead (filled symbols) conditions. Data were collapsed across reference ITD due to the lack of any statistically significant differences between these conditions. Means and standard error bars are based on the six data points (three at each reference ITD).

C. Localization dominance

Figure 4 shows a sample data set for the pointer task. For brevity, we will refer to the various experimental conditions in the pointer task using two letters to denote the lateral positions (right, R; center, C; and left, L) of the lead and lag, respectively. The instructions are denoted by which letter is bold (recall that listeners were instructed to match either the right-most or left-most image). The bold letter denotes which of the bursts in the target was farther to the side indicated by the instructions. For instance, in the **R**-C condition, the lead ITD was $+400$ μs (right) and the lag ITD was 0 (center). Since, in isolation, the R stimulus is right-most compared

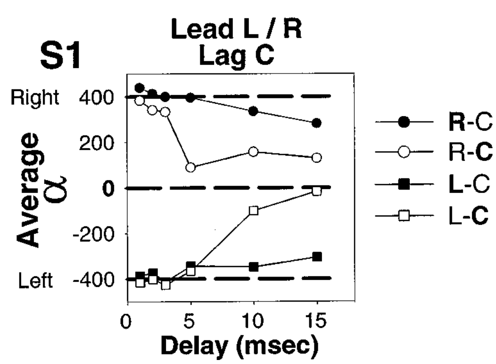

FIG. 4. Example of pointer results for subject S1 at one set of conditions in which the lead was either on the right (400 μs) or left (-400 μs) and lag was at center. The average perceived position (α), based on five repetitions at each condition, is plotted as a function of lead–lag delay. The symbol fill indicates whether instructions were to match the lead (filled) or lag (open). Symbols indicate whether the lead was on the right (circle) or left (square).

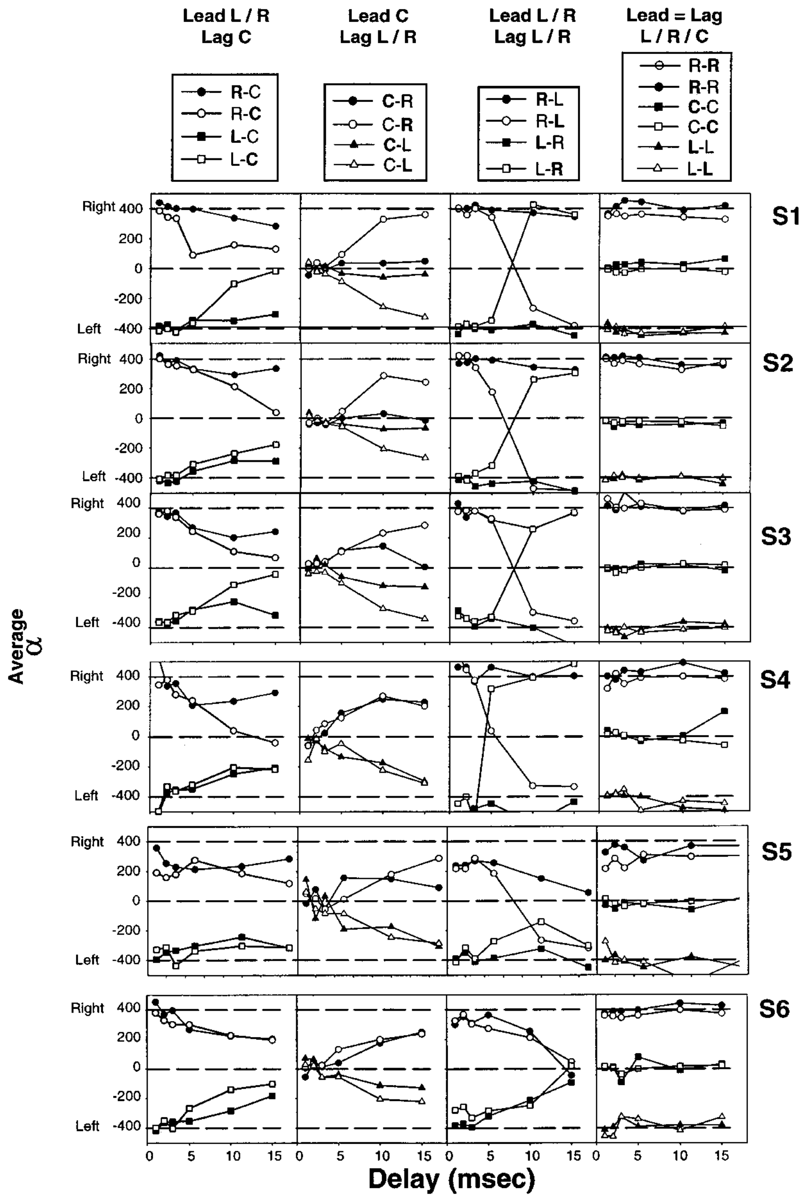

FIG. 5. Pointer results for six listeners portray the average (of five trials) alpha values—the perceived locations (ITDs) under various conditions, at delays 1–15 ms. Each row contains data from one listener. In the legend (top), lead–lag positions are denoted by order, so that R-C denotes lead on right and lag at center. Instructions included cases in which listeners were told to match the ''right-most'' or ''left-most'' auditory image in the event that more than one image was heard; the bold letter indicates whether instructions were consistent with matching the lead or lag. Each column contains data for a set of complimentary conditions. The left column shows cases in which the lead was on either the right (+400 μs) or left (−400 μs), and the lag was always at center. The second column shows cases in which the lead was always at center and the lag was either on the right or left. In the third column, both lead and lag could be on the right or left. In the right-most column, lead and lag were always at the same location, either on the right (R-R), or at center (C-C), or on the left (L-L). The dashed lines within each plot indicate the ITDs for the left, center, and right (−400, 0, 400 μs, respectively).

with the C stimulus, the R is bold when the instructions were to match the right-most. In R-**C** the C is bold because the instructions were to match the left-most. We henceforth refer to a condition such as **R**-C as one for which ''the instructions were to match the lead'' (and, similarly, R-**C** as a condition for which ''the instructions were to match the lag''), even though the instructions were always to match either the left- or right-most sound image.

In the example in Fig. 4, four conditions are shown: two with lead on right and lag at center (**R**-C and R-**C**), and two with lead on left and lag at center (**L**-C and L-**C**). Closed symbols denote cases in which the instructions were to match the lead, and open symbols denote cases in which the instructions were to match the lag. Each horizontal dashed line marks one of the noise burst (either lead or lag) ITDs.

If the listener hears two images at separate locations that are roughly equal to the locations of each burst in isolation, the same stimulus should yield different results depending on the instructions (whether or not the subject can tell the temporal order of the two images). The **R**-C matches would then be near the lead ITD at +400 μs and the R-**C** matches would then be near the lag ITD at 0. However, if the lead dominates localization, both **R**-C and R-**C** stimuli would be heard near the lead ITD at +400 μs, regardless of instructions. Similarly, in the two L-C conditions, if the lead dominates localization, match ITD should fall near −400 μs, independent of instructions. Conversely, if matches fall near the lag ITD, it indicates that directional information from the lag is influencing performance.

In Fig. 4, when instructions were to match the lead, the matched ITD (pointer ITD) was near the lead ITD at all delays. At the shorter delays, the listener matched the lead ITD regardless of instructions, consistent with a strong precedence effect. When instructions were to match the lag, the matched position only approached the lag ITD at 15 ms for the L-**C** condition. In the R-**C** condition, the matched ITD was 100 μs even for a delay of 15 ms, indicating that the lead still carried a great deal of influence in the localization process.

Figure 5 shows the entire data set for the pointer task.

Results show a strong effect of delay and a dependence on the relative ITDs of the lead and lag for all listeners. In this figure, the open and closed symbols should differ if listeners hear two distinct positions. For instance, the open symbols in the left column would fall at 0 μs if listeners matched the position of the lag (independent of the lead). Similarly, the closed symbols should remain at either $+400$ or -400 if listeners matched the position of the lead (independent of the lag).

At short delays, regardless of instructions, all listeners placed the pointer near the ITD of the lead, suggesting that they perceived one location near the lead. As delay increased, different instructions elicited different responses for the same stimulus, although not all listeners perceived two images at longer delays. In addition, the likelihood of perceiving two distinct images depends on the relative ITDs of the lead and lag. Listeners S1–S4 generally heard two separate images for delays equal to or greater than 15 ms. However, some results are asymmetric, most notably for listeners S2 and S4, who heard an image near the lag ITD when the lead was on the right, but not when the lead was on the left. Even at the longest delays measured, listeners S5 and S6 did not appear to hear two separate images. For these subjects, results are roughly independent of instructions: the open and closed symbols are near the lead ITD at short delays and are approximately midway between the lead and lag ITDs at longer delays.

When the lead was at center and lag lateral (to either the right or left; second column) three listeners (S1–S3) heard one image for delays ranging from 1 to 5 ms and two images at longer delays. The other three listeners (S4–S6) heard one image whose location was near the lead at short delays and midway between the lead and lag at longer delays.

Finally, when the lead and lag were on opposite sides (± 400 μs; third column), four listeners (S1–S4) localized two distinct images at the longer delays. The matched positions of the two images were essentially equal to the locations at which the lead and lag bursts would be perceived when presented in isolation, indicating that the lead and lag images did not interact for these subjects and conditions. Listener S5 showed some asymmetry. S5 matched two distinct images when the lead was on the right or left, but the spatial separation of these images was much smaller when the lead was on the left. Listener S6 never matched two distinct locations.

D. Match performance near echo threshold

The ability of listeners to locate two distinct images does not seem to be directly related to their subjective reports of whether one or two images are present. Fusion data (Fig. 2) show that many of the listeners reported hearing two sounds at delays near 5 ms; however, at these delays the same listeners matched a single location near the lead, independent of instructions (Fig. 5). Thus, it appears that localization dominance persists to longer delays than fusion.

To illustrate this point, Fig. 6 plots estimated matched ITD at the fusion echo threshold delay (found by interpolating matched ITDs across delay). Each plot shows data from one listener. For every lead/lag ITD and instruction combination, the matched position is plotted as a function of lead ITD. The symbol and fill indicate whether instructions were to match the lead (squares) or the lag (open circles). Filled circles are used for matches in which lead and lag ITD were equal and instructions were expected to have no effect. In Fig. 6, if the lead ITD completely dominated perception, the data would fall along the diagonal, independent of instructions or lag ITD. In other words, the matched ITD would be roughly equal to and highly correlated with lead ITD, independent of instructions. If two locations were perceived, the squares would generally be expected to fall nearer the diagonal and the open circles to be independent of lead ITD value.

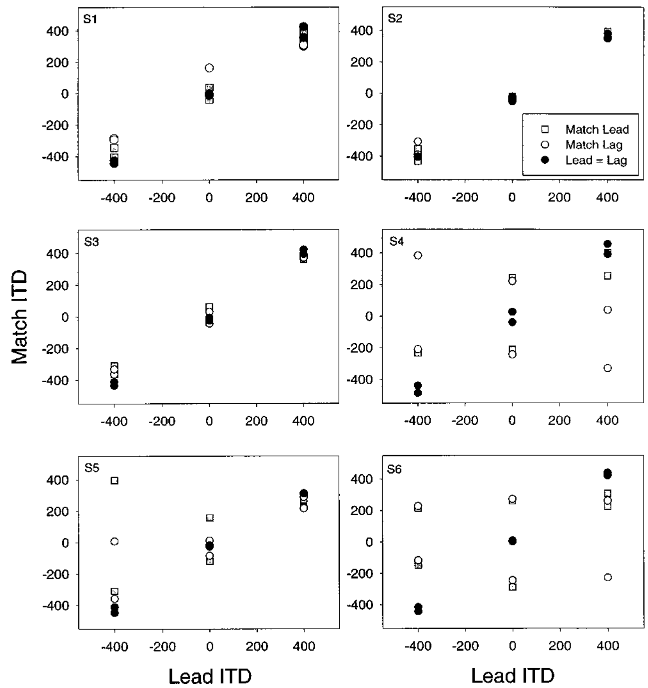

FIG. 6. Estimated matched ITD at the fusion echo threshold delay (found by interpolating matched ITDs across delay). Each plot shows data from one listener. For every lead/lag ITD and instruction combination, the matched position is plotted as a function of lead ITD. The symbol and fill indicate whether instructions were to match the side closer to the lead ITD (squares) or the lag ITD (open circles). Filled circles are used for matches in which lead and lag ITD were equal and instructions were expected to have no effect. For each condition, two data points appear with the same symbol, representing different values of lag ITD.

Table II shows correlation values between lead or lag ITD and match ITD at fusion echo threshold when instructions were to match lead or lag. For some subjects, the cor-

TABLE II. Correlations between lead (or lag) ITD and matched ITD, when instructions were to match the lead (or lag).

Subject	Lead ITD and instructions to match lead	Lead ITD and instructions to match lag	Lag ITD and instructions to match lead	Lag ITD and instructions to match lag
1	0.99	0.97	0.06	0.18
2	1.00	0.99	−0.01	0.01
3	0.99	0.99	0.06	0.10
4	0.91	0.17	0.16	0.94
5	0.57	0.88	0.57	0.30
6	0.65	0.39	0.64	0.90

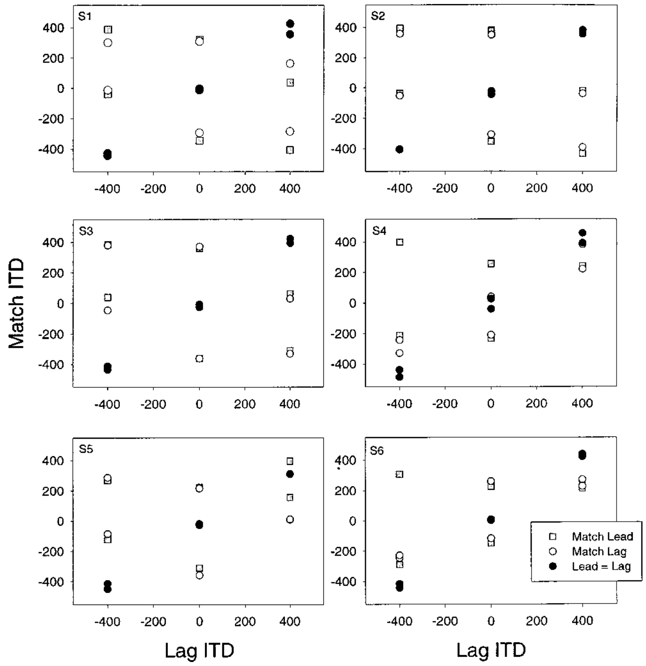

FIG. 7. Data from Fig. 6, replotted as a function of lag ITD.

relation with lead ITD was quite high regardless of instruction. For other subjects, these correlations were more modest. For all subjects, correlations were low between lag ITD and matched ITD regardless of instructions. These results suggest that, at fusion echo threshold, listeners were primarily utilizing directional cues contained in the lead.

The data are replotted in Fig. 7 as a function of lag ITD to further illustrate this point. If data fell along the diagonal, it would indicate that subjects heard a single location near the lag ITD, independent of lead ITD. If subjects heard two independent images at the lead/lag locations, open circles would fall on the diagonal (be highly correlated with the lag ITD) and squares would show little dependence on (be essentially uncorrelated with) lag ITD. Both the lack of structure in the data in the plot and the low correlation between matched ITD and lag ITD (Table II) further confirm that precedence is strong at echo threshold.

For three listeners (S1, S2, S3) the lead was clearly dominant, with the correlation between lead ITD and matched ITD close to 1.0 regardless of instructions (see Table II). Listener S4 had high correlations (a) between lead ITD and matched ITD when instructions were to match the lead, and (b) between lag ITD and match ITD when instructions were to match the lag. This result suggests that S4 was able to match the location of either source. Both S5 and S6 showed only moderate correlations with either lead or lag ITD. S5 showed some asymmetry, with matches dominated more by the lead when the lead ITD was to the right (+400 μs) than to the left (−400 μs).

E. Model estimate of precedence weight based on pointer results

The metric c (described in Shinn-Cunningham *et al.*, 1993) was calculated to quantify the relative influence of the lead and lag in localization. According to the model, the value of c is estimated by

$$c=(\alpha_p-\tau_2)/(\tau_1-\tau_2),$$

where α_p is the matched ITD and τ_1 and τ_2 are the lead and lag ITDs, respectively, for a given condition. A c value of 1.0 indicates that precedence is complete and that the lead dominates lateralization entirely. A c value of 0.5 indicates that the lead and lag both contribute equally to localization perception. A c value of 0 indicates that the lag dominates lateralization completely. In our study, instructions varied, and listeners were told to match either left or right images (see Figs. 4 and 5 for details). When told to match the lag, a c value of 0 would be expected if listeners heard two distinct images, one near the lead ITD and one near the lag ITD. If listeners were told to match the lead and a distinct image was heard near the location at which the lead would be heard in isolation, a c value of 1 is expected. Finally, if the lead and lag form a single image, then c should fall between 0 and 1 and be independent of instructions.

In Fig. 8, c values for each listener are shown as a function of delay for combinations of conditions in which the lead was lateral (L or R) and lag at center (left column), the lead at center and lag lateral (middle column), or both lead and lag were lateral (right column). The fill indicates the instructions; open and closed symbols reflect conditions in which instructions were to match the lead and lag, respectively.

Four listeners (S1–S4) showed strong precedence at delays less than 5 ms. Regardless of instructions, they matched the lead location and c values were near 1. For these subjects, as delays increased, precedence weakened. When instructed to match the side of the lead, c was high, indicating that these listeners heard the lead with little influence of the lag. However, as delay increased, two distinct images were heard. When instructed to match the lag, c was less than 0.5, indicating that subjects heard a second image that was influenced more by the lag ITD than the lead ITD. For listeners S5 and S6, c rarely fell below 0.5, indicating strong precedence at all delays tested.

The data also suggest that precedence was weaker when the lead–lag ITD difference was large. To illustrate this point, we calculated the difference between c values for pairs of conditions in which the lead ITD was identical, instructions were consistent, but the magnitude of the lead–lag ITD difference was either 800 or 400 μs. For example, we found the difference in the calculated c values for the condition **L**-R and the condition **L**-C for each subject and delay. Similar comparisons were made for **R**-L versus **R**-C, L-**R** versus L-**C**, and R-**L** versus R-**C**. For each subject, these differences are plotted in Fig. 9 as a function of delay when instructions were to match the lead. Within each plot, differences between left-center and right-center are shown separately. If the lag interferes with the lead more when lead and lag are spatially close, then the difference should tend to be positive, since we would expect c to be nearer to 1 when the lead–lag separation is 800 μs. Similar computations were conducted for the match-lag conditions, but are not plotted; statistical analyses of the data are, however, included (see Table III).

Results show that when listeners were instructed to match the lead, c values tend to be larger (precedence is

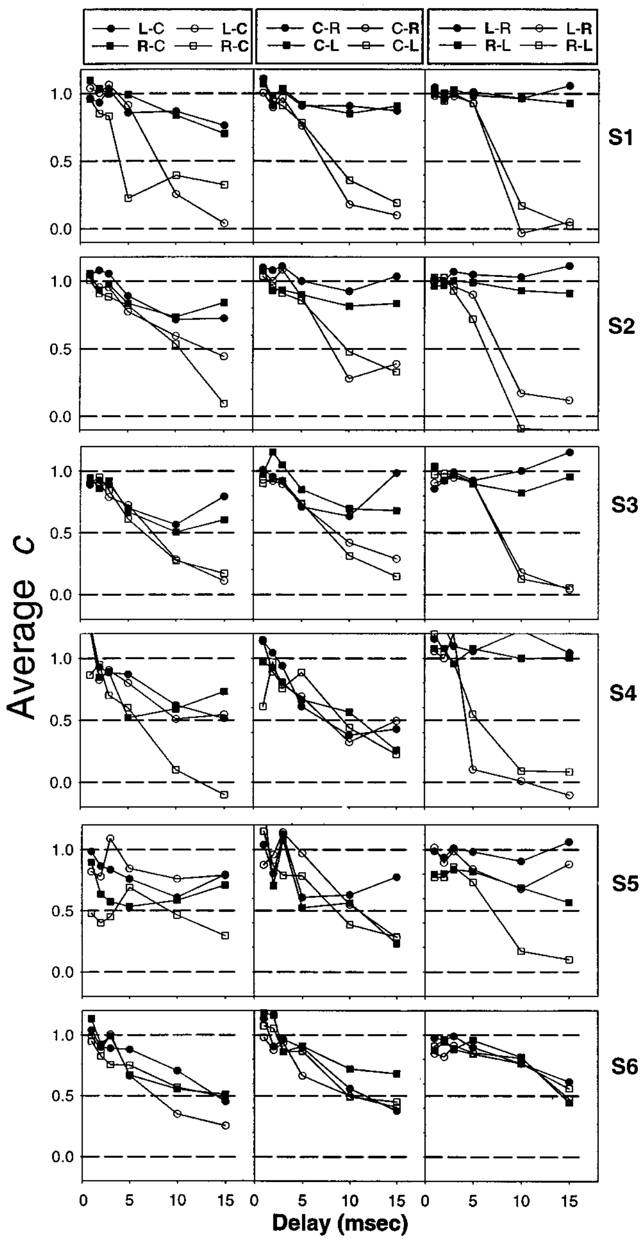

FIG. 8. Average c values (based on five repetitions) as a function of delay. Each row shows data for one listener. Each column contains conditions with different combinations of positions for the lead and lag. Left column: lead was lateral (L or R) and lag at center. Center column: lead at center and lag lateral. Right column: both lead and lag lateral (see legends at top of columns). For each condition, the burst that listeners were instructed to match is indicated in bold. The fill indicates the instructions; closed and open symbols reflect conditions in which instructions were to match the lead and lag, respectively.

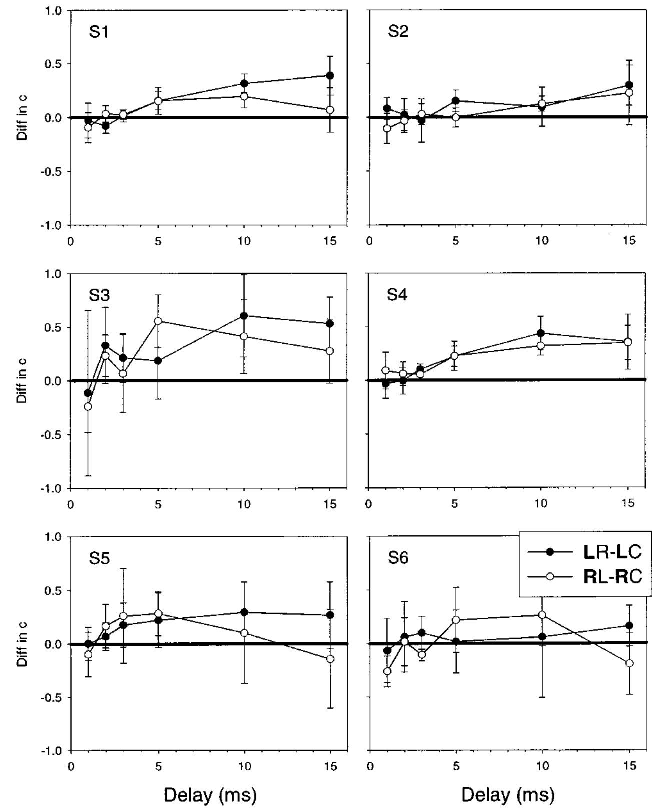

FIG. 9. Difference in c values for large (800 ms) and moderate (400 ms) difference between lead and lag ITD. For each subject, delay, and lateral source location, the c value calculated when the absolute lead–lag ITD separation is small is subtracted from the c value when the lead–lag separation is large. Each panel shows results for a different subject. Error bars show standard deviation in the differences. To the extent that spatial separation results in less influence of the lag on the perceived location of the primarily lead source image location, these differences will be positive.

stronger) when the lead–lag separation is 800 μs compared to 400 μs. This effect is especially pronounced at longer delays. This finding suggests that interference from the lag on the lead image is greater when the lead and lag are spatially close. However, when listeners were instructed to match the lag, there was no consistent difference between c values for the 800- and 400-μs lead–lag separations, suggesting that the strength of the interference of the lead on the primarily lag image was independent of spatial separation.

These observations were confirmed statistically. Left–right symmetry was assumed in a statistical analysis of the c values (e.g., by combining data for conditions **L**-R and **R**-L). For each subject, the pairs of conditions whose differences are plotted in Fig. 9 were compared using one-tailed, paired t tests to evaluate whether there was a statistically significant effect of the spatial separation of lead and lag on c. The same analyses were conducted for match-lag conditions, although the raw data are not shown in Fig. 9. Results from these analyses are shown in Table III, where comparisons yielding $p<0.001$ are indicated (X). Statistically significant differences were observed in four listeners for the match-lead conditions, and only for intermediate and long delays. Significant differences for the match-lag condition were only observed for one listener at one delay (S1, 10 ms).

In summary, when lead and lag are spatially near one another, localization dominance does not abruptly disappear; rather, a single image moves away from the lead gradually before breaking into two images, one of which grows towards the lead and one which grows towards the lag as delay increases. When lead and lag are spatial far apart (Fig. 8, right column), any second image is very near the lag ITD and is relatively unaffected by the lead ITD.

IV. DISCUSSION

Wallach *et al.* (1949) introduced the term ''precedence effect'' to describe the finding that when two pairs of di-

TABLE III. Test of significance ($p<0.001$) of difference in c values when subjects are instructed to match the source position on the side of the lead burst (A) or lag burst (B). In (A), c values for conditions **L**-R and **R**-L were compared to c values for conditions **L**-C and **R**-C in a one-tailed, paired t test. In (B), c values for conditions L-**R** and R-**L** were compared to c values for conditions L-**C** and R-**C** in a one-tailed, paired t test. Individual subject results are given in initial rows; results across subjects are shown in the bottom row.

	Delay (ms)					
Subject	1	2	3	5	10	15
(A)						
1	...	...	...	X	X	...
2	...	...	...	...	...	X
3	...	...	...	...	X	X
4	...	...	...	X	X	X
5	...	...	...	...	...	...
6	...	...	...	...	...	...
Across subs	...	...	...	X	X	X
(B)						
1	...	...	...	...	X	...
2	...	...	...	...	...	...
3	...	...	...	...	...	...
4	...	...	...	...	...	...
5	...	...	...	...	...	...
6	...	...	...	...	...	...
Across subs	...	...	...	...	...	...

chotic clicks are presented with a brief delay, they are fused into a single auditory image whose perceived direction is dominated by the interaural cues of the leading click pair. This result offered a simplified and elegant analogy to the perception of simple sounds in reverberant spaces, where information concerning the source reaches the ears first and is followed by information from the reflections or echoes. The obvious conclusion was that the auditory system minimizes confusion regarding the true location of the source by attributing greater perceptual weight to the first-arriving wavefront and minimizing the influence of later-arriving reflections. This phenomenon has also been attributed to mechanisms involved in localization dominance (e.g., Divenyi, 1992; see Litovsky *et al.*, 1999). While interaural differences in time and intensity as well as spectral cues are all important in directional hearing, the focus of the present study was on comparing various measures related to precedence, with a focus on interaural time cues.

Over the years, investigators have studied not only localization dominance, but also related perceptual phenomena using the leading–lagging stimulus paradigm. The other measurements include identifying conditions under which the sounds are perceptually fused and determining the extent to which directional changes in the location of the lagging source can be discriminated. These various measures of the perception of stimuli consisting of a direct sound and a later-arriving reflection have all been included under the umbrella term ‘‘precedence effect.’’ Although it is assumed that there is a strong relationship among these different effects, the extent to which they are mediated by the same auditory mechanisms is unclear. To address this question, the present study systematically compared all three phenomena in the same listeners.

In this discussion we first compare our data to results from previous studies, then consider the relationship between the different tasks used in the current study, and finally discuss why it may be appropriate to view the precedence effect not as a mechanism for suppressing echoes, but as a more general process for enabling robust localization.

A. Basic findings and relation to previous work

Fusion results were generally in agreement with previous reports: at short delays (<5 ms) listeners heard one fused sound image, and as the delays increased a second source emerged. The delay at which subjects perceived two sounds on 70.7% of the trials (echo threshold) varied across subjects, although the extent of the variability observed here has not been previously reported. For click stimuli measurements made in free field, echo thresholds have been in the range 5–10 ms (Ebata, 1968; Freyman *et al.*, 1991; Yang and Grantham, 1997a). In our study, thresholds for five subjects fell near or within this range; however, subject S6 had echo thresholds (45–50 ms) significantly longer than any previously reported for click stimuli (for a review, see Litovsky *et al.*, 1999). We cannot eliminate the possibility that long echo thresholds might reflect unusual central auditory processing, not unlike that reported for localization dominance in listeners with temporal lobe epilepsy (e.g., Hochster and Kelly, 1981). However, all previous studies report measurements for only a handful of subjects, and relatively little is known about the range of echo thresholds in the population at large. It is therefore premature to rule out the possibility that the ‘‘normal’’ range of echo thresholds for click stimuli can extend to 50 ms, at least when measured under headphones.

Discrimination results in the present study are in agreement with previous reports in which performance was measured at numerous delays (e.g., Zurek, 1980; Tollin and Henning, 1998; Stellmack *et al.*, 1999). For lag discrimination thresholds, the general phenomenon is illustrated with extremely high ITD jnd's at short delays. The difficulty that listeners encounter in extracting directional information from the lag is thought to reflect a suppressive mechanism that is activated by the presence of the lead. This suppressive mechanism strongly suppresses lag information at brief delays; at longer delays, performance improves as the suppressive influence of the lead becomes less effective. Lead discrimination results further suggest that, while listeners are able to ignore lag information at short delays, at longer delays the lag becomes increasingly more intrusive. This finding is consistent with one previous report (Stellmack *et al.*, 1999) which found that at long delays not only is the lag not suppressed but the lag interferes with the ability to extract lead information more than the lead interferes with the lag. However, this asymmetry (or antiprecedence) is thought to arise because subjects are (1) uncertain about the temporal order of the two auditory events, and (2) tend to be biased towards responding to the more recent stimulus in the pair.

Localization dominance measures using the pointer technique are more extensive here than in previous reports performed either using headphones (Zurek, 1980; Shinn-Cunningham *et al.*, 1993) or in free field (Leakey and Cherry, 1957; Snow, 1954; Haas, 1951; Litovsky *et al.*, 1997). Although there are few existing parametric data for comparison, current results are generally consistent with previous reports: localization dominance is strongest at delays of 1–5 ms and weakens thereafter (for review, see Litovsky *et al.*, 1997). Unfortunately, our data set did not include delays in the range between 5 and 10 ms, which was the delay range across which lead dominance changed most dramatically for most subjects. The current data are also consistent with a previous report (Shinn-Cunningham *et al.*, 1993) which suggested that the dominance exerted by the lead is stronger when the lead and lag ITDs are similar and weaker for larger spatial separations. A similar effect was relatively strong in four (S1–S4) of our six subjects. This finding suggests that both temporal and spatial separation between lead and lag affect the strength of the precedence effect.

Current data are unique from two standpoints. First, the individual variability observed in localization dominance has not been previously reported. Although localization dominance is thought to be most effective for click stimuli at 1–5 ms, two of our listeners did not recover from this effect by 15 ms. Both of these listeners had high fusion echo thresholds (one of the subjects had an extremely large echo threshold; see above). Since instructions and testing protocol was identical for all subjects, we tentatively conclude that the widely accepted duration of the suppressive window (of 1–5 ms) does not apply to all subjects. It is therefore important that a population study be conducted to determine the range of ''normal'' behavior for localization dominance and to estimate the suppressive temporal window for normal-hearing listeners.

This study is also unique in that it quantifies localization dominance in conditions where two sources are perceived by allowing two different responses to the same stimulus conditions. In a previous study using a similar paradigm (Shinn-Cunningham *et al.*, 1993), only one matched position was measured. As a result, if two sources were heard at the longer delay, it is not clear how subjects would decide to respond to nonfused events, let alone whether their decision rule was consistent. In the current study, the pointer experiment was repeated two times with different instructions (to match either the right- or left-most image). The raw data (Fig. 5) as well as the model estimation of the strength of precedence (Fig. 8) suggest that subjects S1–S4 heard only one spatial location at shorter delays and two separate images at longer delays. However, the second (primarily lag) image was influenced by the location of the lead in several instances, especially for the condition with lag on the right or left and lead at center. Similarly, the ''lead'' image was influenced by the ''lag'' image for some conditions and subjects, particularly when the lag ITD was similar to the lead ITD. For two subjects (S5, S6) two separate images were never perceived, perhaps because these subjects were not tested at delays long enough to reveal this separation.

B. Comparison of the three precedence phenomena

No previous studies have compared performance across all three precedence tasks, and few have compared two. No previous studies have compared localization dominance and fusion results.

1. Localization dominance and discrimination suppression

Only one previous study compared localization dominance and discrimination suppression (Shinn-Cunningham *et al.*, 1993). Results of that study suggest that similar processes govern these tasks, in that discrimination performance could be predicted relatively well from localization dominance measures. In the current study, the two subjects (S5 and S6) who showed the strongest tendency to match only one source location in the localization dominance task also exhibited little change in lag and lead discrimination as a function of delay. These results are consistent with the idea that, for these subjects, localization information from the lead and lag is combined to form a single estimate of source location even for long delays. If positional changes in this single image are the only cues that S5 and S6 could use to perform the discrimination task, the interference from the nontarget burst will be pronounced and discrimination will be relatively poor, independent of delay. In other words, the current study qualitatively supports the view that localization dominance and discrimination suppression are closely related.

2. Fusion and discrimination suppression

Freyman *et al.* (1991) measured fusion and discrimination suppression in the same listeners in free field and concluded that these two aspects of precedence are related. Specifically, Freyman *et al.* found that discrimination performance was significantly above chance at a delay near echo threshold. In this free-field study, Freyman *et al.* (1991) randomly presented the lag from one of two locations, separated by 20°, and measured discrimination performance as a function of delay. These results indicate that subjects are able to extract some directional information from the lag at echo threshold; however, it must be pointed out that the detected spatial change of the lag (20°) was quite large compared with jnd's measured in the present study. The current results indicate that at echo threshold, subjects may be able to extract some directional information from the lag, but this information is combined (interacts) with information from the lead. The lead and lag information form either a single (averaged) spatial estimate or two separate images, each of which is influenced by the spatial information in both bursts. Thus, while the auditory system might be capable of extracting directional information from the lag at the fusion echo threshold, some suppression is still present at those delays and best performance is not reached until longer delays.

In a second attempt to link fusion and discrimination, Yang and Grantham (1997a) compared the same two tasks for a train of lead–lag stimuli which produce what is known as the ''build-up of echo suppression,'' whereby the strength of the precedence effect increases with the number of lead–lag pairs. This effect has been attributed to ''higher-order'' mechanisms that are involved in ongoing assessment of room acoustics (Clifton and Freyman, 1997). Yang and Grantham (1997a) found that fusion is more susceptible than discrimination to the build-up of precedence and concluded that the mechanisms mediating these two aspects of precedence are different.

Our study was not aimed at investigating aspects of the build-up effect. Both discrimination and fusion experiments presented three lead/lag intervals in each trial; however, in the fusion experiment, all three intervals were identical, while in the discrimination (ABX) paradigm, one of the intervals differed in its spatial cues. There is some evidence that build-up is affected by the ''consistency'' of the repeated stimuli (e.g., see Clifton and Freyman, 1997). As a result, there may have been less build-up in the discrimination stimuli compared to the fusion stimuli; however, any difference in build-up is likely to be small given the overall similarity of the stimuli in the discrimination and fusion experiments. We found that fusion breaks down at shorter delays than discrimination suppression. It is possible that with a longer stimulus train, using our psychophysical method, fusion would indeed be stronger than discrimination. Further tests must be conducted to reach a firm conclusion.

3. Localization dominance and fusion

The current results suggest that the delays at which listeners recover from fusion and from localization dominance differ. Although there are intersubject differences observed in both tasks, overall there emerges a consistent story regarding the relative strength of these two aspects of precedence. In general, fusion ends at relatively short delays compared with the localization dominance; at echo threshold listeners are not able to match the location of the lagging source. Intersubject variability also suggests that listeners who recover from fusion at shorter delays also tend to hear two separate positions at shorter delays (the latter always being longer than the former). For instance, the two listeners (S5 and S6) who have unusually high echo thresholds are also least likely to match two independent source locations (based on ''left'' or ''right'' instructions) in the localization dominance task.

As pointed out in the above discussion of fusion and discrimination results, it is known that fusion increases with repetitions of lead/lag stimuli. No one has ever measured whether a similar increase in suppression occurs using localization dominance measures; however, the number of presentations of the lead/lag stimuli differed in the two experiments reported here. In the localization dominance task, the ''target'' stimulus was presented as a train of seven identical lead/lag pairs, whereas in the fusion experiment, comparable stimuli were presented in a train of three identical lead/lag pairs. These differences may contribute to the trend to hear two sound events at lead/lag delays for which only one source image was localized. Further work is necessary to determine whether build-up may contribute to the observed differences between the lag at which two events are perceived and the lag at which two locations are perceived. Nonetheless, current results suggest that intersubject differences in echo threshold are qualitatively similar to intersubject differences in localization dominance.

All results are consistent with a simple model in which lead and lag information interacts perceptually and the strength of the interaction decreases with spatiotemporal separation of the lead and lag. At short delays, lead and lag both contribute to spatial perception, but the lead dominates (to the extent that only one position is even heard). At the longest delays tested, two sounds are perceived, but are not always heard at independent spatial locations. Spatial separation of lead and lag affects the degree to which two images are heard, but has no observable effect on the results of the fusion experiment performed in the current study. Overall, these results suggest that fusion and localization dominance may be mediated by somewhat different auditory mechanisms.

C. General notions regarding the precedence effect

Historically, the precedence effect has been discussed as a mechanism for suppressing directional information from echoes in order to allow robust localization of a sound source. However, there are some aspects of the precedence effect that are inconsistent with a mechanism whose primary purpose is suppression of localization information in echoes.

For instance, echoes can come from virtually any direction, independent of the source direction. However, both current and previous results (Shinn-Cunningham *et al.*, 1993) suggest that the relative directions of the lead and lag affect the strength of the suppression. Specifically, the suppression of the lag is greater when the lead and lag arise from similar directions than when they are spatially separated. In addition, the spectral content of an echo is a filtered version of the original source spectrum, so that there is always significant spectral overlap of the direct sound and any echoes. However, under some circumstances suppression occurs also when there is no spectral overlap of lead and lag (Divenyi, 1992; Shinn-Cunningham *et al.*, 1995).

If the spatial auditory system is capable of resolving the locations of both the lead and lag sources separately (i.e., there is little interference between the directional information in the lead and the lag), then there is little need to suppress lag information to preserve accurate localization of the lead. Current theories of binaural interaction (e.g., see Stern and Trahiotis, 1997) suggest that the interference between directional information from the lead and the lag may be greatest when the lead and lag give rise to similar interaural phase delays (IPDs) and excite overlapping populations of IPD-sensitive neurons. However, such interference will be reduced when the lag excites a distinct, separate population of neurons, allowing both lead and lag to be localized independently. With this analysis, the tendency for suppression to be weaker when lead and lag arrive from very different directions may reflect the fact that in this condition, the lag will cause less interference with estimation of the lead position.

There is growing evidence that localization information is combined across frequency in order to reduce ambiguity in the spatial information within any given narrow band of frequencies (Brainard and Knudsen, 1992; Trahiotis and Stern, 1989; Stern and Trahiotis, 1997). Such cross-frequency integration will be detrimental if spatial information from a lagging source is combined with information from a leading source, particularly if the spectral content of the lead and lag differs.

One interpretation of these results is that the precedence effect is a general process that enables robust localization not only in the presence of echoes, but whenever any competing information from a second source arrives before the direction of a previous source has been computed. This view suggests that echo suppression is a special case of a more general computational mechanism in the spatial auditory pathway for suppressing any information that could be disruptive to spatial auditory perception. In addition, the results suggest that the mechanisms underlying the three phenomena described here might have some general commonality, not merely at the initial stages of processing, but at later stages as well.

The current results lend further support to this view. Results from the localization dominance experiment indicate that the strength of the precedence effect as measured in a localization dominance task varies with spatial separation of lead and lag, consistent with a general mechanism for improving sound localization. Although there are links among fusion, discrimination, and localization dominance, further work is necessary to quantify how these measures relate to one another.

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