Lateralization of noise-burst trains based on onset and ongoing interaural delays

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The lateralization of 250-ms trains of brief noise bursts was measured using an acoustic pointing technique. Stimuli were designed to assess the contribution of the interaural time delay (ITD) of the onset binaural burst relative to that of the ITDs in the ongoing part of the train. Lateralization was measured by listeners' adjustments of the ITD of a pointer stimulus, a 50-ms burst of noise, to match the lateral position of the target train. Results confirmed previous reports of lateralization dominance by the onset burst under conditions in which the train is composed of frozen tokens and the ongoing part contains multiple ambiguous interaural delays. In contrast, lateralization of ongoing trains in which fresh noise tokens were used for each set of two alternating (left-leading/right-leading) binaural pairs followed the ITD of the first pair in each set, regardless of the ITD of the onset burst of the entire stimulus and even when the onset burst was removed by gradual gating. This clear lateralization of a long-duration stimulus with ambiguous interaural delay cues suggests precedence mechanisms that involve not only the interaural cues at the beginning of a sound, but also the pattern of cues within an ongoing sound.
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I. INTRODUCTION

The term "the precedence effect" has come to encompass a wide range of experimental results showing that a 'preceding' sound is more influential than a succeeding sound in binaural lateralization and localization tasks. Early studies demonstrated the greater influence of the leading sound on the in-head lateral position of auditory images created by pairs of binaural pulses (Wallach *et al.*, 1949) and the apparent direction of phantom sound sources created by two loudspeakers emitting coherent delayed signals (Haas, 1951, 1972). Many subsequent studies have extended these observations of the role of the precedence effect to binaural discrimination and detection tasks employing a variety of stimuli and measurement techniques (e.g., Yost and Soderquist, 1984; Shinn-Cunningham *et al.*, 1993; Aoki and Houtgast, 1992; see Zurek, 1987; Litovsky *et al.*, 1999, for reviews).

Despite the pervasiveness and robustness of the precedence effect, the search for compelling and testable theoretical accounts of the various phenomena has proved difficult. Proposals have considered mechanisms at several levels of the auditory system, including abstract weighting mechanisms triggered by rapid onsets (Zurek, 1987) or interaural coherence (Faller and Merimaa, 2004), and central auditory inhibitory networks to accentuate leading stimulus components (Lindemann, 1986a, 1986b; Xia *et al.*, in press). Rapid adaptation in neural structures located between the cochlea and sites of binaural interaction has also been proposed (Hafter, 1997). Hartung and Trahiotis (2001) showed that the adaptation that has been observed in responses of auditory nerve fibers can account for some precedence phenomena seen with transient stimuli.

Studies with longer-duration stimuli composed of trains of transients have provided observations that complicate the task of finding a simple precedence mechanism. Saberi and Perrott (1995) first reported that the lateralization of a 250-ms train of binaural pulses could be controlled by the interaural time delay (ITD) of the very first pair of pulses in the train. Freyman *et al.* (1997) and Balakrishnan and Freyman (2002) extended these finding to trains with ITDs that alternated throughout the stimulus duration (again 250 ms). The fact that the ITD of only the first pulse can control the lateralization of a 250-ms stimulus containing more than 100 subsequent pulses suggests that more is involved than a simple temporally-asymmetric response weighting or onset emphasis.

These results showing the influence of an onset transient on the lateralization of long-duration stimuli are reminiscent of the Franssen effect (Franssen, 1962; Hartmann and Rakerd, 1989; Yost *et al.*, 1997; Dent *et al.*, 2007). In the classic demonstration, a tone is abruptly turned on in one loudspeaker and then gated off gradually while simultaneously being gated on gradually from a second loudspeaker. Remarkably, the tone continues to be localized at the first loudspeaker for an extended period of time after that loudspeaker has been turned off. Similar effects of onset ITDs have also been demonstrated by Kunov and Abel (1981) and Abel and Kunov (1983) with abruptly gated sinusoids pre-

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sented via headphones, and by Hartmann and colleagues' findings on the role of onsets in sound localization in reverberant rooms (Hartmann, 1983; Rakerd and Hartmann, 1985, 1986; Hartmann and Rakerd, 1989).

There are currently no satisfying explanations for the effects of onset transients on the lateralization or localization of long-duration stimuli. Experimental studies have focused on delineating the characteristics of the ongoing part (after the onset) that allow the onset to dominate lateralization. Rakerd and Hartmann (1985) suggested that the *plausibility* of the ongoing interaural cues (in the sense that the ITDs and ILDs could have plausibly come from a single sound source in an anechoic space) is a key factor determining onset dominance. Demonstrations of the power of this characteristic include localization accuracy measurements with tones and noises with varying onset gating rates in reverberation (Rakerd and Hartmann, 1986), and localization measurements showing that the Frannsen effect fails in an anechoic room (Hartmann and Rakerd, 1989).

Another characteristic that has been suggested to be important for onset dominance is the *ambiguity* of the ongoing cues. For both the alternating-ITD stimuli used by Freyman and colleagues and the constant-ITD stimuli used by Saberi and Perrott (1995), multiple interaural delay cues were present throughout. Based on their results with abruptly-gated sinusoids, Buell *et al.* (1991) proposed that lateralization of stimuli with ambiguous ongoing cues (associated with large interaural phase shifts of the sinusoid) might be resolved in favor of the ongoing delay closest to the interaural delay of the onset gating. Freyman *et al.* (1997) adopted the metaphor coined by Buell *et al.* (1991) in suggesting that the auditory system might rely on the initial onset pulse to 'tip the scale' toward one or the other of the ambiguous ongoing cues. Freyman *et al.* (1997) went on to show that dominance of the onset ITD was not observed when the ongoing train lacked the ambiguity from multiple interaural delays, consistent with the notion of scale-tipping.

A third factor suggested to play a role in onset dominance with long-duration sounds is spectral density. Hartmann and Rakerd (1989) noted that the localization of sounds whose ongoing parts had dense spectra was less influenced by the onset transient than were ongoing sounds with sparse spectra. The results of two experiments of Freyman *et al.* (1997) were consistent with the importance of spectral density. First, using the type of pulse-train stimuli employed by Saberi and Perrott (1995), they found that increasing the interpulse interval (lowering the fundamental frequency and increasing spectral density) reduced vulnerability to dominance by onset cues. The second experiment in Freyman *et al.* (1997) found that spectrally-dense inharmonic complexes were more resistant to influence from the onset than were sparse complexes.

The current studies of lateralization were undertaken to test these notions of the ongoing stimulus characteristics that allow onset dominance. The stimuli were easily-manipulated trains of wideband noise bursts. The use of trains of noise bursts allows direct control of the ITD of any binaural burst pair in the train, which is convenient for studying the influence of onset versus ongoing ITDs. Further, such changes in the ITD of an individual binaural burst can be made while maintaining a unitary perceptual image. Unlike pulses, noises bursts allow control of burst-to-burst coherence in the train, which can be used to control the ambiguity and spectral density of the ongoing part. The current experiments explored variations in onset and ongoing ITDs, inter-burst coherence, and envelope onset rate (abrupt versus slow) as factors influencing the dominance of onset cues.

II. EXPERIMENT 1. FROZEN TOKENS

In the five sub-experiments of Experiment 1, the target stimuli were (nominally) 250-ms trains of noise bursts which, on a given trial, were constructed from a single 1-ms token of white noise that was repeated and time-shifted as required. The inter-burst interval from the onset of one burst pair to the next in the train was fixed at 2 ms. Each new trial used a fresh noise token.

The target stimuli are described in terms of the ITD of the first, or 'onset,' burst in a train and the ITDs of the subsequent bursts, which collectively form the 'ongoing' part of the stimulus. The primary experimental variable was τ, the ITD of the first burst. The ongoing part always had a repeating pattern of ITDs that may be related to τ, or may involve independent ITDs

A. Experiment 1-A: Variable alternating ITDs

The purpose of this experiment was to determine the extent to which the ITD at onset controls the lateralization of extended trains with ambiguous ongoing delays. Based on work with click trains from Freyman *et al.* (1997) and Balakrishnan and Freyman (2002), it was expected that the onset ITD would be quite influential. This condition serves as a baseline for comparison with subsequent conditions in which several variables, including inter-burst coherence, were manipulated.

1. Stimuli

In this experiment, ITDs alternated between τ and $-\tau$ throughout the train, where, as always, the first ITD was τ. Figure 1(a) depicts schematically the first few ms of a target stimulus (with abrupt gating). The number inside each burst indicates the identity of the noise token used. In this experiment a single noise token was used within a trial, with a fresh token selected for each new trial. Values of τ ranged from -600 to $+600$ μs in 100-μs steps (positive values of interaural delay indicate that the right stimulus led). Because there was an even number (126) of burst pairs in the 250-ms train, the ITD of the last burst pair was $-\tau$. Noise burst trains were presented in one condition with abrupt gating (i.e., instantaneous rise and fall) and in another condition with a 125-ms linear (in amplitude) gating rise and fall, leaving no steady-state portion. The spectral and perceptual characteristics of these stimuli are described in a footnote.[1]

The stimuli were generated on a personal computer with a 24-bit sound card, low-pass filtered at 8.5 kHz, attenuated (TDT PA4), and delivered through TDH 39 headphones via a headphone amplifier (TDT HB5) and a passive attenuator at a level of 61 dB SPL as measured in a 6 cm^3 coupler. The

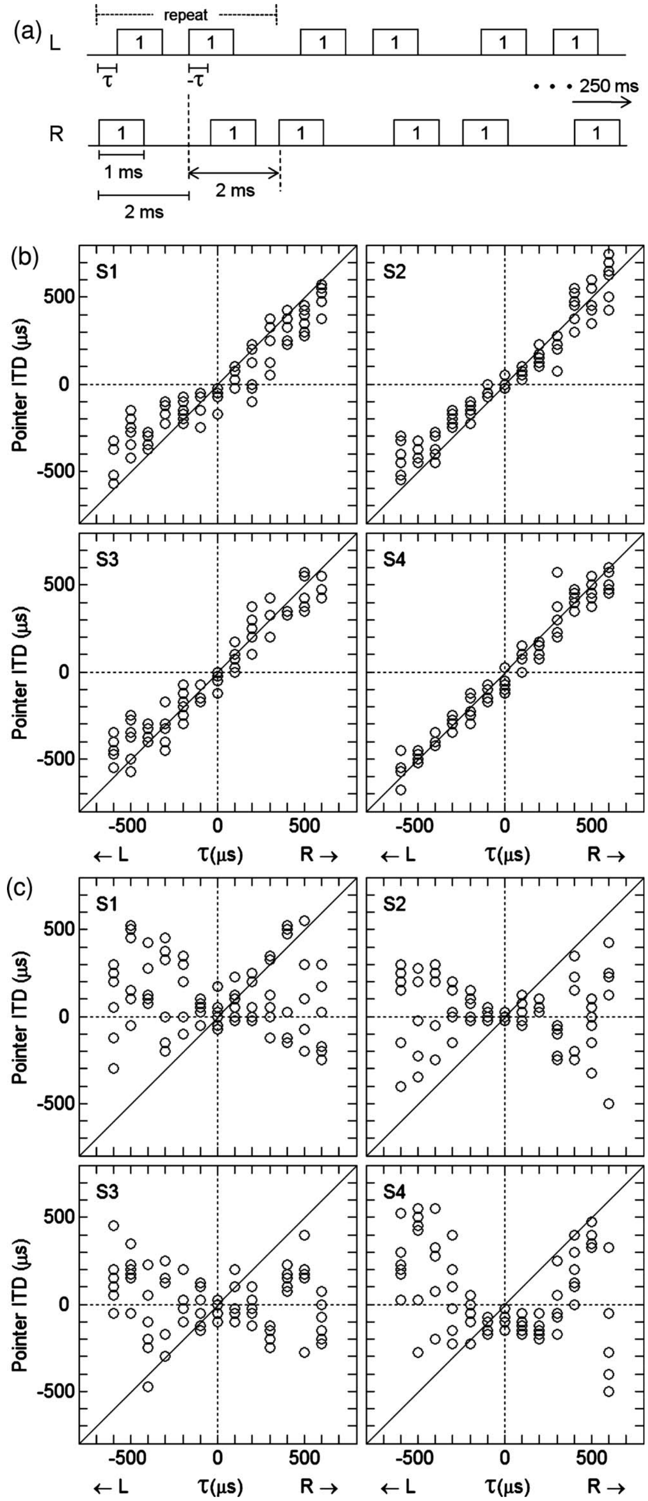

FIG. 1. Stimuli and results for Experiment 1-A. (a) The first few ms of the 250-ms binaural noise burst train (when gated abruptly) is illustrated schematically. Each rectangle represents a burst of white noise. The label ('1' in this case) indicates the identity of a noise token. In this experiment the noise burst trains were constructed using a single frozen token on each trial. The ITD τ of the first burst in the train is the main experimental variable. In this experiment bursts after the first had ITDs that alternated between $-\tau$ and $+\tau$. The time span indicated by 'repeat' indicates the pattern of ITDs that is repeated for the remainder of the stimulus. In this experiment the stimuli themselves repeat exactly, but in subsequent experiments that will not necessarily be the case. (b) Results with rectangular gating. Pointer adjustments from four listeners plotted as a function of τ. The diagonal line indicates y=x. At each value of τ tested there are six data points (which sometimes overlay each other). (c) As in (b), but with gradual (125-ms) rise/fall gating.

target stimuli were generated and presented at a 20 kHz digital-to-analog (D/A) conversion rate. For each experimental run, an acoustic pointer stimulus was generated, consisting of a 50-ms binaural burst of white noise with a linear 5-ms rise and fall. The pointer was presented at a 40 kHz D/A conversion rate, permitting a resolution of 25 μs in the pointer ITD, which was controlled by pre-padding zeros in one channel or the other. The level of the pointer was 57 dB SPL.

In the majority of conditions described in this paper the listeners were four female graduate students (S1–S4), aged 23–27, all with hearing thresholds $<=20$ dB HL at all audiometric frequencies from 250 through 6000 Hz. In a few conditions (in Experiments 1-C and 2-C), those listeners were supplemented by three more students (S5–S7) and by the first author (S8) aged 54, all meeting the stated audiometric criteria.

2. Procedure

All experiments were conducted in a double-walled sound-treated booth (IAC 1640). Listeners wore the headphones and used a computer keyboard to control the ITD of the pointer. The keys "M" and "N" increased the ITD by 125 and 25 μs, respectively, while the keys "V" and "B" decreased the pointer ITD by 125 and 25 μs, respectively. Thus, listeners could move the intracranial image of the pointer to the right or left in either large or small steps as needed. The target and pointer alternated continuously during a trial with an onset-to-onset period of 1 s. The listener's task was to move the image of the pointer until it matched the intracranial position of the target as closely as possible before entering the final match by pressing the "X" key. Listeners were instructed to take care not to approach the target position only from one side, but to move the pointer image to both sides of the target before zeroing in on the final match. There was no time limit imposed on this process. The initial pointer ITD was varied randomly from trial to trial through a range of ± 500 μs. The 13 values of τ were randomized and used once each in a run of 13 trials. A new trial began immediately after the preceding one ended. Listeners removed the headphones and took a short break between runs. Each subject completed six runs at each value of τ. Unless stated otherwise, all general stimulus generation and procedural details were the same for all experiments in this paper.

3. Results

Pointer matches obtained in the abrupt-gating condition are plotted in Fig. 1(b). Each panel shows individual matches for a listener as a function of τ, the ITD of the first burst pair and every second pair thereafter. For each listener, the matches were consistently and strongly related to τ. Thus, it is quite clear that although the ongoing parts of the target stimuli were ambiguous (because of both their continuously alternating ITDs and the coherence between tokens), the lateral positions of the stimuli were not ambiguous and were strongly determined by τ. This result is consistent with those of both Freyman *et al.* (1997) and Balakrishnan and Freyman (2002), who had included similar conditions (± 500 μs alternations) using pulse stimuli. It is also consistent with Saberi and Perrott's (1995) result showing dominance of the very first ITD in a long train of binaural pulses with a fixed ITD in the ongoing part.

Figure 1(c) shows the results obtained with slow (125-ms) gating of the target stimuli. Matches in this condition were quite variable across repetitions, with no clear dependence on τ. This is the result expected based on the ambiguous ITDs of the ongoing parts of the target stimuli. It is not clear from the slow-rise data themselves whether listeners perceived a diffuse poorly lateralized auditory image for each trial, multiple images, or an image whose lateral position was clear but varied from trial to trial. Interviews with the listeners suggested the first of these possibilities.

As shown in Fig. 1(c), removal of the abrupt onset and offset apparently eliminated the basis for lateralization that existed in the previous condition. To verify that it was the slow onset and not the slow offset that was responsible for ambiguous lateralization, three subjects listened informally to ± 500 μs alternating stimuli that had only slow rises or only slow falls. All three reported difficulty lateralizing the slow-rise stimuli, but found the slow-fall stimuli to be easily and well lateralized according to the onset ITD. The result of this experiment is consistent with the notion that the onset ITD cue dominates lateralization by 'tipping the scale' in favor of the matching ongoing ITD.

B. Experiment 1-B: Ongoing ITD = ±500 μs

The purpose of this experiment was to determine if it was necessary that the onset ITD match one of the alternating ongoing ITDs—as it did in the previous experiment–in order for the onset ITD to dominate lateralization.

1. Stimuli

As shown in Fig. 2(a), the ITDs during the ongoing part alternated between +500 and −500 μs, while τ was varied from −500 to +500 μs in 100 μs steps. The second burst pair in the train, the one that began the alternation between plus and minus 500 μs, was always right-leading. The stimuli were abruptly gated.

2. Results

The pointer adjustments shown in Fig. 2(b) indicate that lateralization of the target stimuli again followed the onset ITD, even though it did not match one of the ITDs in the ongoing stimulus. This result is inconsistent with the notion that the role of the onset ITD is to tip the scale toward one of the ongoing ITDs.

C. Experiment 1-C: Ongoing ITD = 0 μs

This experiment was similar to the preceding one, but here the ongoing ITD was fixed at zero throughout the train. In the preceding experiment, the absolute value of τ was less than or equal to that of the ongoing ITD. The purpose here was to determine whether nonzero onset ITDs could control lateralization when the ongoing ITD was fixed at 0 μs.

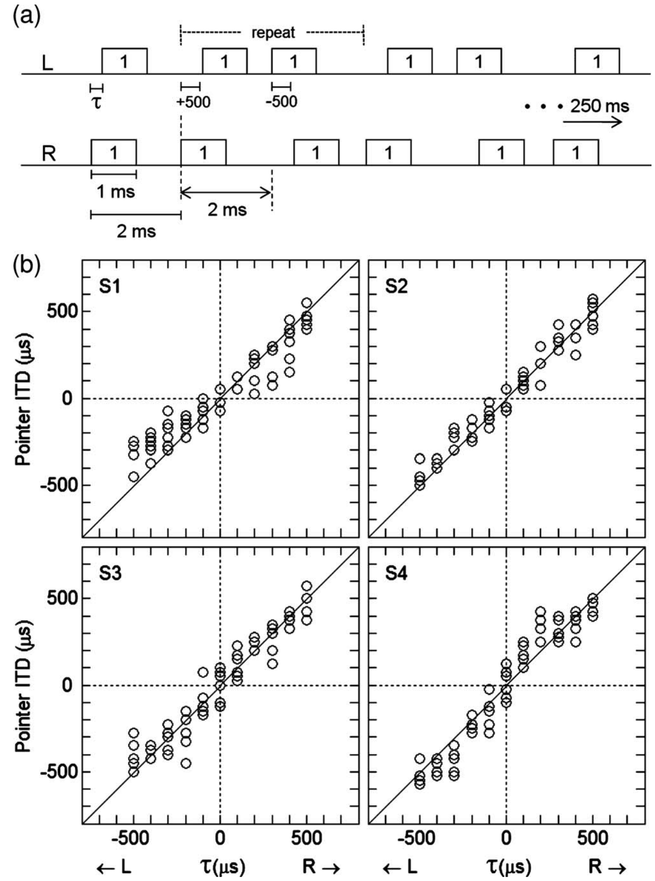

FIG. 2. Stimuli and results for Experiment 1-B. (a) As in Fig. 1(a), but in this experiment the ITDs of the bursts after the first pair alternated between +500 and −500 μs, while τ was varied from −500 to +500 μs in 100-μs steps. The second burst pair in the train, which began the alternation between ± 500 μs, was always right leading. Stimuli were abruptly gated. (b) Pointer adjustments from four listeners plotted as a function of τ.

1. Stimuli

As shown in Fig. 3(a), the ongoing ITD was fixed at 0 μs while the onset ITD varied. The stimuli were abruptly gated.

2. Results

Unlike the results for the previous experiments, lateralization in this one differed somewhat across listeners [see Fig. 3(b)], with some showing more onset dominance than others. For example, the matches of Subjects 1 and 2 revealed a nearly-constant location of the target near the auditory midline, with only a slight dependence on τ. The data of Subjects 3 and 4, on the other hand, showed lateralization that was more strongly dependent on the ITD of the onset burst, but that was still weaker than that seen in the previous experiments for these two subjects. Because of this variability across the original four subjects, two more young normal-hearing listeners were recruited (and trained with the stimuli used in Experiment 1-A, showing similar results to the others in that experiment). Their results are shown as Subjects 5 and 6 in Fig. 3(b). The pointer matches of these two additional subjects are similar to those of Subjects 1 and 2. Note also that, in contrast to the results shown in Fig. 1(c), the repeatability of subjects' matches here was fairly good even

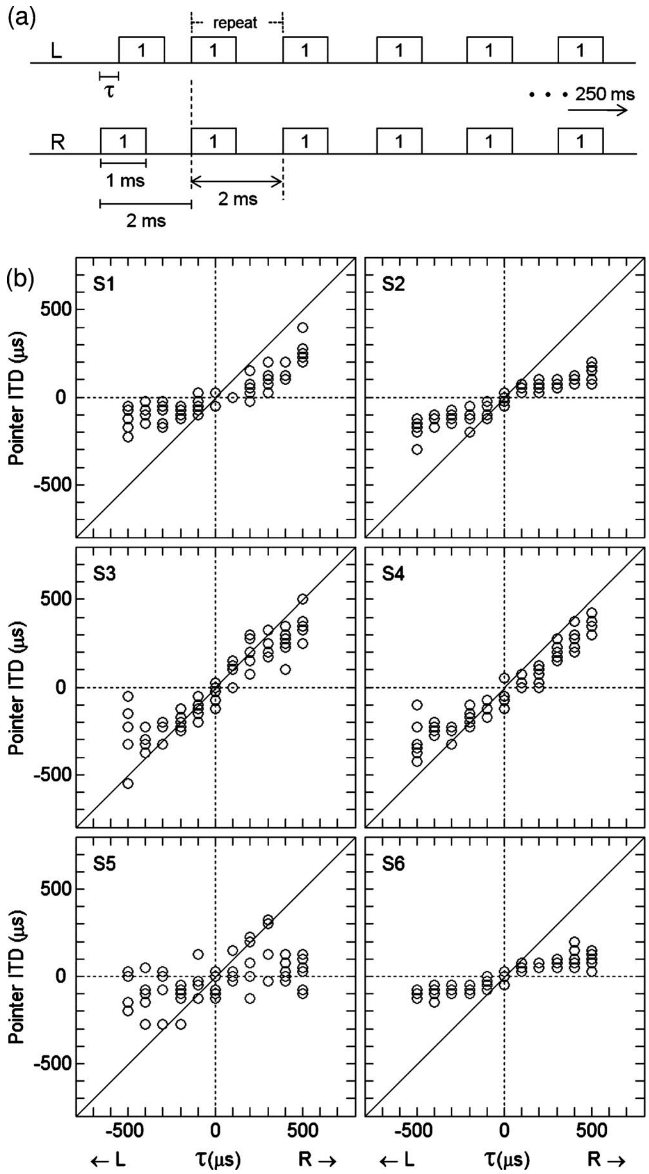

FIG. 3. Stimuli and results for Experiment 1-C. (a) As in Fig. 1(a), but in this experiment the ITDs of the bursts after the first pair were fixed at 0 μs, while τ was varied from -500 to +500 μs in 100-μs steps. (b) Pointer adjustments from six listeners plotted as a function of τ.

though onset dominance was weak in both cases. Overall, it must be concluded from these results that onset dominance in lateralization is not consistently strong for all listeners when the ongoing ITD is fixed at 0 μs. The next two experiments were attempts to determine whether ongoing ITDs at other values would show a similar pattern.

D. Experiment 1-D: Ongoing ITD$=\pm\alpha$

In this experiment the ongoing ITD alternated between equal and opposite values that varied independently of the onset ITD. Only Subjects 2 and 3 participated.

1. Stimuli

The stimuli for this experiment are shown schematically in Fig. 4(a). The onset ITD varied from -500 to +500 μs in 100 μs steps, for a total of 11 conditions. In separate sub-

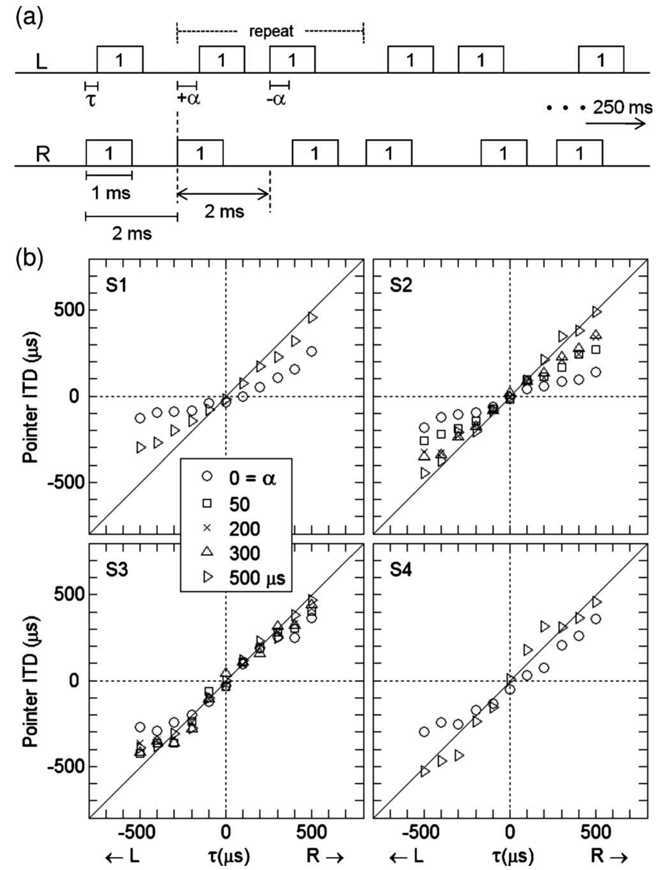

FIG. 4. Stimuli and results for Experiment 1-D. (a) As in Fig. 1(a), but in this experiment the ITDs of the bursts after the first pair alternated between $+\alpha$ and $-\alpha$ μs, while τ was varied from -500 to +500 μs in 100-μs steps. The second burst pair in the train, which began the alternation between plus and minus α, was always right leading. Stimuli were abruptly gated. (b) Pointer adjustments from four listeners plotted as a function of τ. Only mean matches are shown for each condition. Note that the results for α=0 and α=500 μs were taken from Experiments 1-C and 1-B, respectively.

conditions, the ongoing ITD (α) alternated between $\pm$300, $\pm$200, $\pm$100, and $\pm$50 μs (beginning with right-leading). Thus, both subjects ran four sets of conditions with six matches for each condition and onset ITD as before. The stimuli were abruptly gated.

2. Results

In order to demonstrate the main features of the data, only the mean matches for each condition are shown in Fig. 4(b). In addition to the new conditions, the means for the two parametrically-related conditions ($\alpha=\pm500$ μs from Experiment 1-B, and α=0 from Experiment 1-C) are also shown. The data for Subjects 1 and 4 at α=0 and $\pm$500 μs have been included in the figure as well. For Subject 3, the effect of the onset ITD was fairly strong even with α =0 μs, as shown earlier in Fig. 3(b), and there was little dependence on α. Subject 2, however, showed a clear effect of α, with onset dominance increasing as both τ and α increased. Subjects 1 and 4 showed patterns indicating contributions of α that were intermediate between those of the other two subjects.

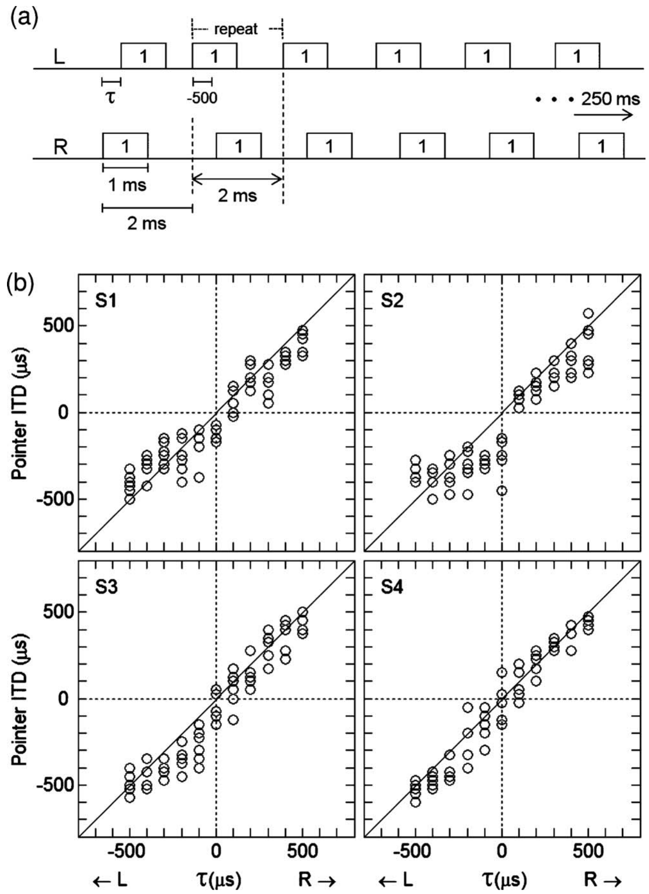

FIG. 5. Stimuli and results for Experiment 1-E. (a) As in Fig. 1(a), but in this experiment the ITDs of the bursts after the first pair were fixed at −500 μs, while τ was varied from −500 to +500 μs in 100-μs steps. (b) Pointer adjustments from four listeners plotted as a function of τ. Similar results (not shown) were obtained when the ongoing ITD was fixed at +500 μs.

E. Experiment 1-E: $\alpha = -500\ \mu s$

This experiment used a fixed nonzero value of ongoing ITD. The purpose was to help understand the result from Experiment 1-C that the fixed ongoing ITD of 0 μs, not the onset ITD, tended to dominate lateralization for most of the listeners. It was not clear whether it was the fact that the ongoing ITD was fixed or whether it was zero (i.e., central) that contributed most to this effect. This experiment was an attempt to distinguish between these two possibilities by using a fixed but lateral ongoing ITD. All four of the original listeners participated.

1. Stimuli

Figure 5(a) shows a schematic of the stimuli. The ongoing ITD was fixed at −500 μs. As before, τ varied from −500 to +500 μs in 100 μs steps. The stimuli were abruptly gated.

2. Results

The matches shown in Fig. 5(b) indicate that lateralization was strongly determined by the ITD of the initial burst pair. A full set of measurements was also obtained with an ongoing delay of +500 μs with equivalent results. This finding is consistent with those obtained for pulse trains by Saberi and Perrott (1995) and Freyman *et al.* (1997). These results, along with the results of some subjects in Experiments 1-C (zero ongoing delay) and 1-D (alternating ongoing delays), all suggest stronger onset dominance with larger-magnitude (more lateral) ongoing ITDs.

III. EXPERIMENT 2. QUAD SETS

Experiment 2 consisted of four sub-experiments designed to determine the role of inter-token coherence in the lateralization of trains of noise bursts. In these experiments the term ‘quad set’ is used to denote a leading binaural pair of bursts and a trailing binaural pair of bursts, constructed from a single noise token. Different quad sets used different, statistically uncorrelated noise tokens. The ongoing parts of the stimuli can be viewed as the sum of a direct train of independent 1-ms noise bursts occurring every 4 ms plus its repetition after a delay. In all the sub-experiments of Experiment 2, the direct sound and the repetition had equal and opposite interaural delays.

A. Experiment 2-A: Variable alternating ITDs

This experiment was a repetition of Experiment 1-A, except that the trains were made from quad sets instead of a single token.

1. Stimuli

Figure 6(a) illustrates schematically the first few milliseconds of the noise burst train. The pattern of ITDs was the same as in Experiment 1-A, with ITD alternating between the same values (±τ) throughout the train. Values of τ ranged from −600 to +600 μs in 100-μs steps. The difference from Experiment 1 was that the same token of noise burst was not used throughout the train. Instead, a fresh token was used for each quad set, containing one alternation of positive and negative ITDs. As before, fresh tokens were used for each trial. Stimuli were presented with abrupt gating in one condition and with slow, 125-ms, linear gating in another condition. The spectral and perceptual characteristics of these stimuli are described in a footnote.[2]

2. Results

The pointer matches for stimuli presented with abrupt gating, displayed in Fig. 6(b), are, for each listener, reliable and strongly dependent on τ. These results are consistent with the data obtained with abruptly-gated frozen tokens in Experiment 1-A. In another full set of measurements in which the ITD of the lagging burst in each quad set was set to zero, instead of −τ, equivalent results were obtained.

The pointer matches obtained with stimuli presented with slow gating, shown in Fig. 6(c), also indicated a strong dependence on τ. This result is unlike that obtained with frozen tokens in Experiment 1-A, where slow gating caused

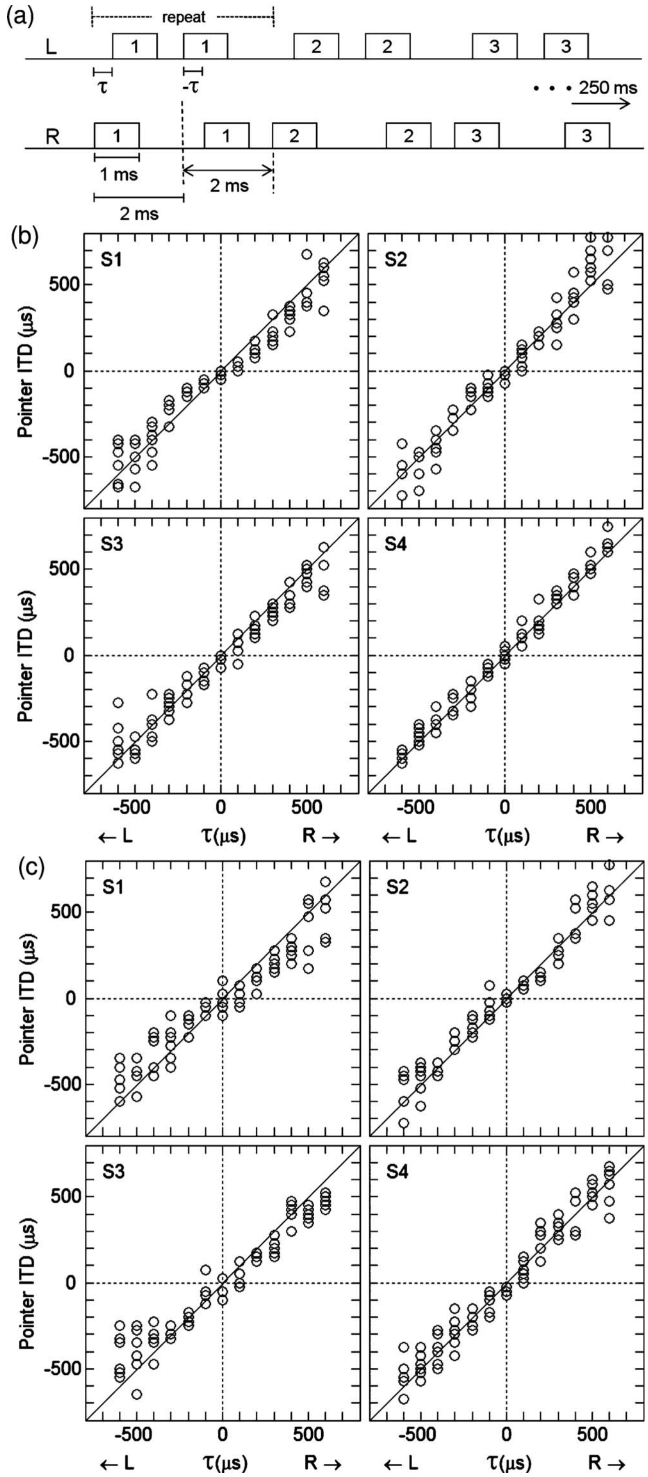

FIG. 6. Stimuli and results for Experiment 2-A. (a) As in Fig. 1(a), but in this experiment the noise-burst trains were constructed using "quad sets," in which a single frozen tokens were repeated only once in each channel before a new token was introduced. ITDs alternated between $-\tau$ and $+\tau$, with τ varying from -600 to +600 μs in 100-μs steps. (b) Results with rectangular gating. Pointer adjustments from four listeners plotted as a function of t. (c) As in (b), but with gradual (125-ms) rise/fall gating.

lateralization to become unclear and variable. It appears that the onset ITD is not necessary for clear lateralization of these quad-set stimuli. The leading ITD in each quad set, τ, not the ITD of the onset burst, seems to be the key determinant of lateralization.

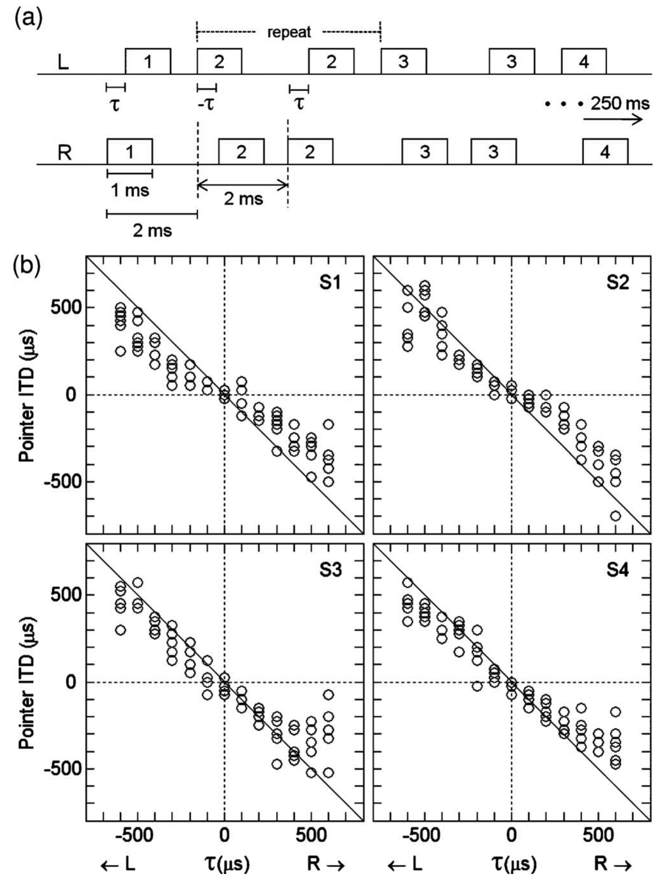

FIG. 7. Stimuli and results for Experiment 2-B. (a) As in Fig. 6(a), but in this experiment the quad sets were initiated with the second burst of the train with an ITD of $-\tau$, with τ varying from -600 to +600 μs in 100-μs steps. (b) Pointer adjustments from four listeners plotted as a function of τ.

B. Experiment 2-B: Variable alternating ongoing ITDs with an opposing onset ITD

This experiment tested whether an onset burst with an ITD equal to that of the lagging burst in each quad set could control lateralization.

1. Stimuli and Procedures

This experiment used the same stimuli as in Experiment 2-A, except that a single binaural burst (with a fresh noise token) was inserted at the beginning of the stimulus [see Fig. 7(a)]. The ITD of this initial burst, τ, was equal to the ITD of the lagging burst pair–and opposite the ITD of the leading burst pair–in each quad set. The total number of pairs was kept the same, so the last of the 126 pairs still had an ITD opposite the onset. The stimuli were presented with abrupt gating.

2. Results

The pointer matches in Fig. 7(b) indicate that lateralization was dominated not by the onset ITD τ, but by the ITD of the leading burst in each quad set. Although a close comparison of these results to those in Fig. 6 reveals that dominance was slightly reduced here (the data are not as closely clustered around the diagonal in Fig. 7), the basic result is largely consistent with those of Experiment 2-A in which removal of

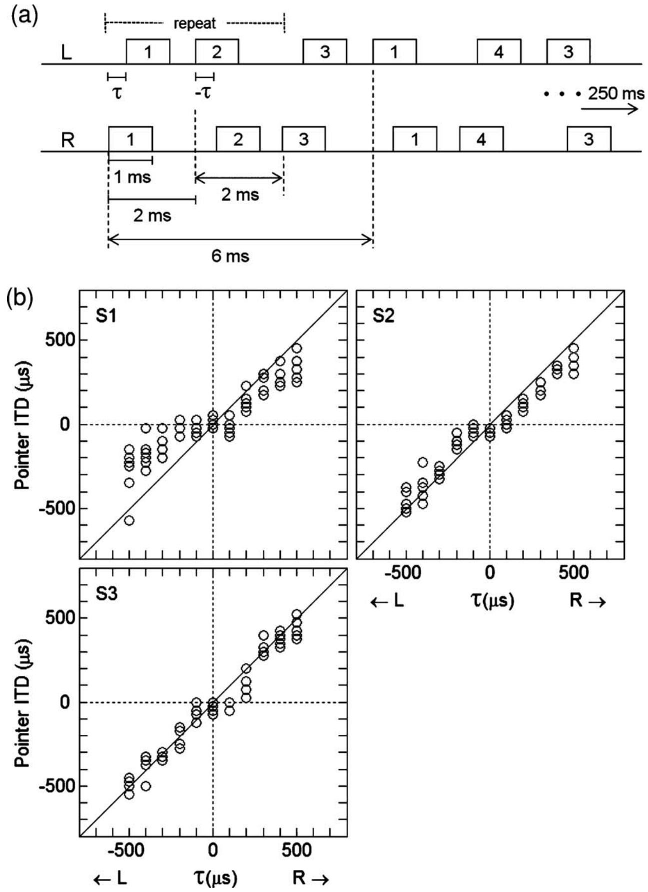

FIG. 8. Stimuli and results for Experiment 2-C with a 6-ms reflection delay. (a) As in Fig. 6(a), but in this experiment the quad sets were split up so that the second instance of each token followed 6 ms (rather than 2 ms) after the onset of the first instance of each token, with different tokens interleaved in between. τ varied from -500 to $+500$ μs in 100-μs steps. (b) Pointer adjustments from three listeners plotted as a function of τ.

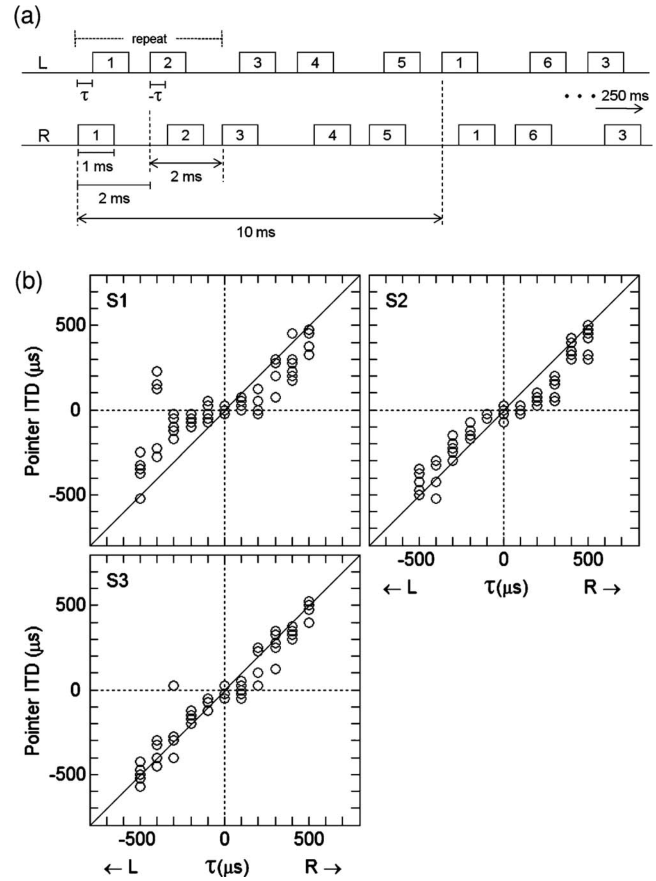

FIG. 9. Stimuli and results for Experiment 2-C with a 10-ms reflection delay. (a) As in Fig. 8(a), but in this experiment the second instance of each token followed 10 ms (rather than 6 ms) after the onset of the first instance of each token, with different tokens interleaved in between. (b) Pointer adjustments from three listeners plotted as a function of τ.

onset cues by gradual gating had no effect on lateralization. Both results suggest that for these quad-set stimuli, the ITD at stimulus onset had little importance. Rather, lateralization was controlled by the initial ITD in each quad set.

C. Experiment 2-C: Delayed reflections, abrupt gating

The ongoing parts of the stimuli used in the experiments thus far can be viewed as being composed of a direct noise burst followed by a reflection, followed by another direct burst, followed by its reflection, and so on. These stimuli were highly structured for experimental purposes, as opposed to simulating any naturally-occurring conditions. Natural sound sources are not always brief bursts and, even if they were, their reflections do not necessarily arrive before the next direct burst. In this experiment, the ‘reflection’ (i.e., the lagging repetition of an earlier token) was delayed further in time from the ‘direct sound’ (the leading token) to simulate somewhat more realistic situations and to determine at what delays a second instance of a token would still be processed as a reflection and not as a new direct sound.

1. Stimuli and Procedures

The noise burst trains, schematized in Fig. 8(a) and Fig. 9(a), contained ITDs that alternated between $\pm\tau$ as in Experiment 2-A. The difference here was that the second binaural burst in each quad set was delayed by either 6 ms (Fig. 8) or 10 ms (Fig. 9), during which time tokens from others quad sets intervened. The stimuli were abruptly gated. In Fig. 8(a), note that, in order to preserve temporal regularity of the train, token 2 was inserted as the lagging partner of a nonexistent leading token 2. Likewise, in Fig. 9(a), tokens 2 and 4 were inserted for the same purpose.

2. Results

The pointer matches shown in Figs. 8(b) and 9(b) indicate that lateralization was again clearly dominated by τ, the ITD of the onset burst and of the leading burst in each quad set. In comparison to the corresponding results with a 2-ms reflection delay (Fig. 6(b)), Subject 1 showed slightly reduced dominance with a 6-ms delay; with a 10-ms delay Subjects 2 and 3 also showed slightly reduced onset dominance.

D. Experiment 2-D: Delayed reflections, slow gating

Because the stimuli in the preceding experiment were abruptly gated, the relative contributions of onset and ongoing ITD cues could not be separated. In this experiment both the abrupt- and the slow-gating conditions were examined.

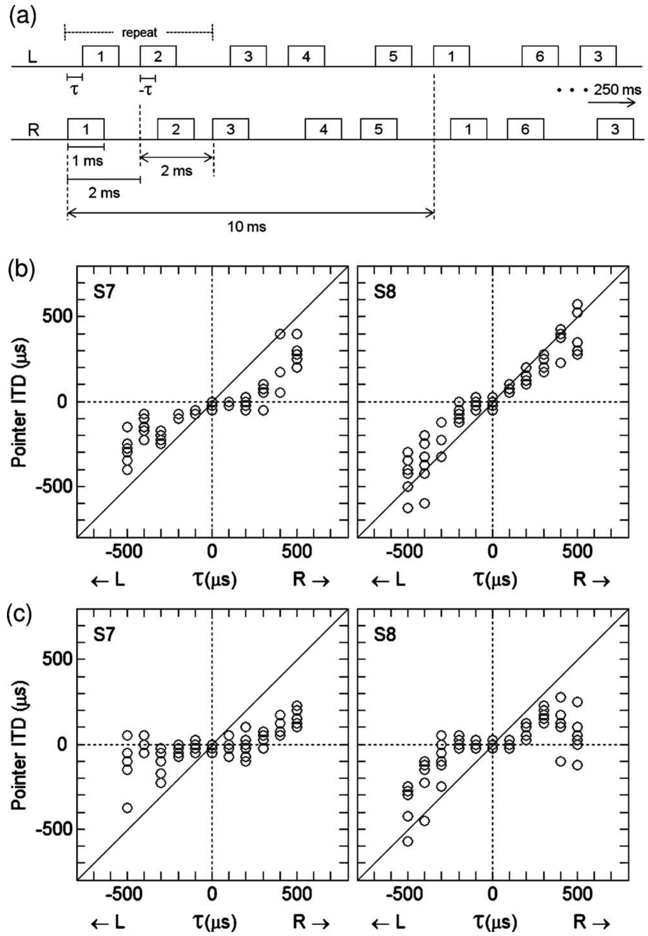

FIG. 10. Results for Experiment 2-D with a 10-ms reflection delay. (a) The stimuli are as in Fig. 9(a), shown here abruptly gated. Pointer adjustments of two subjects are shown in panel (b) for abruptly-gated stimuli and panel (c) for slowly-gated stimuli.

Because this experiment was run after the other subjects were no longer available, two new subjects served as listeners.

1. Stimuli and procedures

The noise burst trains [Fig. 10(a)] were like those used in Experiment 2-C, with the second binaural burst in each quad set delayed by 10 ms. The stimuli were either abruptly or slowly gated.

2. Results

The pointer matches shown in Figs. 10(b) repeat with these new subjects the abrupt-gating condition of the preceding experiment [Fig. 9(b)]. Both subjects showed dominance by τ, the ITD of the onset burst and of the leading burst in each quad set, with Subject 8 showing a clearer effect than Subject 7. The corresponding results with slow gating [Fig. 10(c)] showed a mixed result. While removal of the abrupt onset diminished the strong dependence on τ, there remained a partial dependence that must be attributed to the cues in the ongoing part of the stimulus. The subjects reported that the auditory images of the slowly-gated stimuli were less distinct than those of the abruptly–gated stimuli.

IV. DISCUSSION

This section will first summarize the most important findings from the individual experiments. The different results obtained across conditions will then be used to support the notion that the precedence effect consists of three fundamentally different phenomena. Finally, relationships of the new data to the literature will be considered, as well as their impact on existing theories of the precedence effect.

A. Summary of main findings

1. Experiment 1: Frozen tokens

(a) The lateralization of trains of binaural frozen noise bursts with symmetrically-alternating ITDs was dominated by the ITD of the very first burst pair in the train. When gradual rise and fall times were imposed to severely attenuate the onset, the noise burst trains could not be reliably lateralized.

(b) The ITD of the initial burst pair did not have to match either of the alternating ongoing ITDs in order for it to be the primary determinant of lateralization. However, some subjects showed stronger onset dominance with larger-magnitude (more-lateral) ongoing ITDs.

(c) Onset dominance with non-alternating ongoing ITDs was also stronger and more robust across listeners when the ongoing ITD was more lateral than when it was more central. With an ongoing ITD of 0 μs, most listeners did not show strong onset dominance.

2. Experiment 2: Quad sets

(a) The lateralization of noise burst trains with alternating ITDs was not dominated by the ITD of the onset burst when fresh burst tokens were used for each pair of alternations (quad sets). Instead, lateralization was controlled by the ITD of the first pair in the quad set. The key difference between frozen tokens and quad sets is the coherence among tokens. Frozen tokens possess multiple, ambiguous interaural delays between every neighboring burst, while quad sets possess multiple delays only among the components within a quad. A perceptual correlate of this physical difference is that the ongoing parts of the frozen stimuli could not be lateralized (in most cases) without the onset transient (i.e., when a slow rise/fall was imposed) while the ongoing parts of the quad set stimuli could be lateralized without an onset transient.

(b) The delay between leading and lagging burst pairs in each quad set could be extended to 10 ms, with fresh bursts interleaved, and still demonstrate a dominance by the ITD of the leading burst pair in the quad set. This dominance was reduced when the stimuli were slowly gated, suggesting a contribution from the onset.

B. Three phenomena

Discussion of the relation of the present results to previous results and conjectures can best be organized around the three phenomena that seem to underlie the various findings that are associated with the precedence effect. A variety of results, the present ones included, suggest that the following three phenomena are distinct and that they contribute to the various manifestations of the effect.

The first phenomenon is the lateralization dominance of a leading transient over others that follow within a time period of about 1–10 ms. Experimental data documenting this effect are plentiful (e.g., Wallach *et al.*, 1949; Zurek, 1980; Yost and Soderquist, 1984; Shinn-Cunningham *et al.*, 1993; Litovsky and Shinn-Cunningham, 2001; Zurek and Saberi, 2003). The fact that lateralization dominance is obtained equally whether the leading transient is coherent or not with the trailing one (Zurek, 1980; Zurek and Saberi, 2003) suggests that this is a true onset emphasis, and not the result of the patterns of interaural difference cues that can result with coherent transients (Tollin and Henning, 1999). Although the present study did not employ brief transient stimuli, the transient precedence effect enters into the discussion.

The second phenomenon is the lasting control that an abrupt onset can exert over the lateralization (or localization) of a long stimulus. Instances of this phenomenon are the Franssen effect (Franssen, 1962; Hartmann and Rakerd, 1989; Yost *et al.*, 1997, Dent *et al.*, 2007), results of experiments using tones and pulse trains (Kunov and Abel, 1981; Abel and Kunov, 1983; Saberi and Perrott, 1995; Freyman *et al.*, 1997; Balakrishnan and Freyman, 2002), and the results of the present Experiment 1, where the lateralized image created early in the stimulus (presumably by the transient effect just described) persists through the long-duration ongoing part which, by itself, may or may not be poorly lateralized (or localized). Because there has thus far been no distinction between Franssen's (1962) original observations and later, and similar, effects, we will refer to this phenomenon simply as the Franssen effect.

The third phenomenon does not rely on abrupt onsets and so will be called an 'ongoing precedence effect.' Examples of this effect are seen here most clearly in the results obtained with the slow-rise quad-set stimuli used in Experiment 2-A, as well as in previous studies employing long-duration overlapping stimuli. (Zurek, 1980; Braasch *et al.*, 2003; Dizon and Colburn, 2006).

Although this categorization has been made in terms of phenomena that are presumed to be distinct, depending on stimulus conditions one might observe one type of precedence effect or a combination of more than one. For example, using speech and music, Haas (1951, 1972) measured leading-sound dominance out to about 50 ms, beyond which the lagging sound was heard as a distinct echo. Because of the presence of transients in his source sounds, his results may reflect a combination of Franssen and ongoing precedence effects. In the current Experiment 2-B, an onset transient was placed in opposition to the lead ITD in the ongoing quad-set stimuli. The ongoing ITD appeared to dominate, but the data do not lie as neatly on the negative diagonal in Fig. 7 (Experiment 2-B) as they do on the positive diagonal in Fig. 6 (Experiment 2-A). This may indicate some contribution from the initial ITD. Experiments 2-C and 2-D together demonstrate that the lateralization of stimuli with "reflections" delayed by up to 10 ms—which are lateralized reasonably well according to the ongoing ITDs—is nevertheless strengthened further by strong onset cues. This indicates a contribution of the Franssen effect for stimuli partially lateralized according to the ongoing precedence effect. Still longer delays could change further the relative contributions of Franssen and ongoing precedence effects. Dizon and Colburn (2006) found lateralization dominance with slow-gated white noise to be completely eliminated at a delay of about 20 ms. It is not known whether lateralization of such stimuli could be partially controlled by strong onset cues.

C. Impact on prior conjectures and models

1. The Franssen effect

The present experiments provided tests of some of the notions about the relation between onset and ongoing cues in the Franssen effect and added new insights into the characteristics of ongoing stimuli that make them susceptible to onset dominance. The results of Experiment 1 do not support the metaphor mentioned in the Introduction (Buell *et al.*, 1991; Freyman *et al.*, 1997) that a strong onset serves to 'tip the scale' toward one or another of multiple ongoing ITDs. Although an abrupt onset was shown to be necessary for onset dominance with frozen tokens, listeners' pointer adjustments followed the onset ITD, whether or not it corresponded to one of the ongoing ITDs. This is not to say that the 'tipping the scale' principle does not apply to the tones used by Buell *et al.* (1991) or other related stimulus conditions, but the idea does not appear to provide a general explanation that applies to the current stimuli.

Nor do the present results support an exclusive role for spectral density as a characteristic of the ongoing stimulus in the Franssen effect. Studies by Hartmann (1983), Hartmann and Rakerd (1989), and Freyman *et al.* (1997) had found decreasing onset dominance for stimuli with denser spectra, i.e., noise or complex tones with closely spaced harmonics, relative to complexes with harmonics spaced more widely (by at least 1.5 bark in Hartmann, 1983). However, the results from the current Experiment 1 show marked differences in susceptibility to onset dominance for ongoing stimuli with identical spectral densities. The difference in susceptibility seen between an ongoing ITD of 0 μs (not very susceptible) and an ongoing ITD of 500 μs (very susceptible) suggests that factors other than spectral density are also important.

A more consistent account might be based on the ambiguity of the ongoing part. In the fixed 500-μs ITD condition there is an opposing −1500 μs ITD across the interburst interval, whereas in the fixed 0-us condition the ITD across the interburst interval is 2000 μs. In the terms of Stern *et al.* (1988), there is a smaller difference in centrality, and presumably more ambiguity, between different delays in the former case (−500, 1500) than in the latter (0, 2000). It is possible that the difference between 1500 and 2000 μs is of no consequence, and that the important difference is only between 500 μs and 0 μs. This could perhaps be evaluated in future experiments by manipulating the interburst delay independently of the fixed ongoing ITD.

Inconsistencies between ITDs and ILDs may present another form of ambiguity that contributes to the vulnerability of the ongoing sound to control by the onset, and may explain the difference found between responses to the two ITDs mentioned above. While ILD was not manipulated in these experiments, it did have a constant value of 0 dB, which would have led to a centered percept in the absence of an ITD. In the case of the fixed 500-μs ITD, the 0-dB ILD is inconsistent with the ITD, potentially creating ambiguity that leads to vulnerability to onset cues. In contrast, when the ITD is 0 both type of cues point consistently to the center, and this may decrease the vulnerability to onset dominance.

The notion that ongoing ambiguity is a necessary condition for the Franssen effect to be observed is consistent with several past observations. Hartmann and Rakerd (1989) found that the Franssen effect is abolished either if the experiment is conducted in an anechoic chamber or if noise is used in place of a tone. Either manipulation makes the ongoing part less ambiguous, or more plausible as the result of a single anechoic source, than the ongoing part in the original condition of a tone in a reverberant room. In the present study, ongoing delays that were smaller in magnitude (and hence less subject to ambiguous interpretation as to which side leads) led to a weakening of onset dominance.

2. The ongoing precedence effect

It is natural to consider whether an explanation of the ongoing precedence effect can be found among the mechanisms that have been proposed for the transient effect. Models that employ inhibition triggered by abrupt onsets (Zurek, 1987) or binaural adaptation (Hafter and Dye, 1983) would need to be specified in more detail in order to test their predictions. Nevertheless, it may be productive to consider the similarities of the current results to those described by Hafter and colleagues in studies of binaural adaptation. Those studies demonstrated that, within a train of high-frequency pulses, improvements in ITD discrimination with increasing duration were less than optimal, implying that additional pulses made smaller and smaller contributions to the aggregate binaural information carried by longer and longer stimuli. Their parsimonious interpretation of that finding, which was later directly confirmed by Saberi (1996), was that later clicks made smaller contributions to ITD sensitivity. This adaptation can be 'reset,' with some restoration of sensitivity, by a number of manipulations, including the insertion of a silent gap between two pulses (Hafter and Buell, 1990). It is conceivable that the introduction of new tokens in the quad set stimuli continually resets the binaural system, releasing adaptation for each new token. However, this account would have to deal with the results of the present Experiment 2-C showing that the lead ITD continues to contribute strongly even when uncorrelated bursts intervene between the leading and lagging bursts in a quad. Such intervening bursts would presumably reset the system.

Another approach is that taken by Tollin and Henning (1999) who proposed that analysis of the patterns of steady state interaural time and level difference cues with coherent transients was sufficient to account for lateralization performance. Similar patterns exist with the long-duration stimuli that evoke the ongoing precedence effect. However, unlike the special 3-component transients analyzed by Tollin and Henning (1999), analysis of the present stimuli has yet to disclose interaural cues favoring either the leading or the lagging ITD.

Faller and Merimaa's (2004) model is fairly well-specified but has been tested thus far only with transients and speech, which exhibits extreme modulation and contains transients. Their coherence-based selection mechanism is not expected to favor one ITD over another ITD in stimuli designed to evoke only the ongoing precedence effect.

Braasch and Blauert (2003) found that peripheral adaptation, which accounts nicely for transient precedence effects (Hartung and Trahiotis, 2001), failed to predict their ongoing-noise lateralization data. Even when stimuli are abruptly gated (Balakrishnan and Freyman, 2002), the contribution from the adaptation-enhanced onset is minimal after averaging over a long-duration stimulus. Initial attempts by the present authors to apply similar models to the slowly-gated quad-set stimuli also revealed slight degrees of sidedness favoring the leading ITD. This advantage was so small, however, that it could be offset by less than 0.5 dB of attenuation of the leading burst in each quad set. It is possible that a full parametric exploration of the peripheral model would reveal more pronounced asymmetry favoring the initial ITD, so the possibility of a solution based on peripheral mechanisms cannot be ruled out.

Braasch and Blauert (2003) have provided the only model that has had some success in accounting for an ongoing precedence effect. They modified Lindemann's (1986b) model with the addition of a module that incorporates interaural level-based excitation-inhibition with temporal inhibition. This model could reproduce their psychoacoustic lateralization results with noise stimuli with bandwidths up to 800 Hz. Whether Braasch and Blauert's (2003) model can account for the present ongoing precedence effect data is currently being studied, along with other approaches.

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[1]The spectral and perceptual characteristics of the frozen stimuli used in Experiment 1 are dominated by the periodicity of the ongoing parts. There are two categories of stimuli. The stimuli used in Experiment 1-A, 1-B, and 1-D had ongoing parts with alternating ITDs. In those cases, the ongoing part of either the L or R stimulus was composed of a direct 1-ms sample of noise and a repetition of that noise added after a delay, β, that could differ between L and R depending on experimental conditions. In the frequency domain the magnitude spectrum of the ongoing part of these L or R stimuli can be viewed as the product of a source composed of a series of equal-magnitude components every 250 Hz, and a comb filter with spectral period $1/\beta$ resulting from the delayed repetition. The L and R stimuli have a common buzzy pitch equivalent to 250 Hz, but slightly different timbres when their comb filters differ. The stimuli used in Experiments 1-C and 1-E had ongoing parts that were simply periodic at 2

ms. Their spectra had components at integer multiples of 500 Hz, with a buzzy pitch of the same frequency.

[2]The spectral and perceptual characteristics of the ongoing parts of the quad-set stimuli of Experiment 2 differ from the frozen noise-burst trains of Experiment 1. Because there was no temporal periodicity in the unfrozen trains, there was no harmonic structure to the spectrum and no clear pitch quality for the L and R stimuli heard either separately or together. The ongoing part of either the L or R stimulus in this case was a train of (unfrozen) 1-ms noise bursts occurring every 4 ms, plus a delayed repetition added after β sec. As before, β depended on the experimental conditions and could differ between L and R. The long-term magnitude spectra of the ongoing part of either the L or R stimulus is the product of a white noise spectrum and a comb filter with spectral period $1/\beta$. The L or R ongoing stimuli have the raspy quality of rapidly-interrupted noise, with a slight timbral difference when their comb filters differ.

Abel, S. M., and Kunov, H. (**1983**). "Lateralization based on interaural phase differences: Effects of frequency, amplitude, duration, and shape of rise/decay," J. Acoust. Soc. Am. **73**, 955–960.

Aoki, S., and Houtgast, T. (**1992**). "A precedence effect in the perception of inter-aural cross-correlation," Hear. Res. **59**, 25–30.

Balakrishnan, U., and Freyman, R. L. (**2002**). "Lateralization and detection of pulse trains with alternating interaural time delays," J. Acoust. Soc. Am. **112**, 1605–1616.

Braasch, J., and Blauert, J. (**2003**). "The precedence effect for noise bursts of different bandwidths. II. Comparison of model algorithms," Acoust. Sci. & Tech. **24**, 293–303.

Braasch, J., Blauert, J., and Djelani, T. (**2003**). "The precedence effect for noise bursts of different bandwidths. I. Psychoacoustical data," Acoust. Sci. & Tech. **24**, 233–241.

Buell, T. N., Trahiotis, C., and Bernstein, L. R. (**1991**). "Lateralization of low-frequency tones: Relative potency of gating and ongoing interaural delays," J. Acoust. Soc. Am. **90**, 3077–3085.

Dent, M. L., McClaine, E. M., and Welch, T. E. (**2007**). "The Franssen effect illusion in budgerigars (Melopsittacus undulatus) and zebra finches (Taeniopygia guttata)," J. Acoust. Soc. Am. **122**, 3609–3614.

Dizon, R. M., and Colburn, H. S. (**2006**). "The influence of spectral, temporal, and interaural stimulus variations on the precedence effect," J. Acoust. Soc. Am. **119**, 2947–2964.

Faller, C., and Merimaa, J. (**2004**). "Source localization in complex listening situations: Selection of binaural cues based on interaural coherence," J. Acoust. Soc. Am. **116**, 3075–3089.

Franssen, N. V. (**1962**). *Stereophony* (Philips Technical Library, Eindhoven, The Netherlands).

Freyman, R. L., Zurek, P. M., Balakrishnan, U., and Chiang, Y. C. (**1997**). "Onset dominance in lateralization," J. Acoust. Soc. Am. **101**, 1649–1659.

Haas, H. (**1951**). "Über den einfluss eines einfachechos auf die hörsamkeit von sprache," Acustica **1**, 49–58.

Haas, H. (**1972**). "The influence of a single echo on the audibility of speech," J. Audio Eng. Soc. **20**, 145–159.

Hafter, E. R., and Buell, T. N. (**1990**). "Restarting the adapted binaural system," J. Acoust. Soc. Am. **88**, 806–812.

Hafter, E. R. (**1997**). "Binaural adaptation and the effectiveness of a stimulus beyond its onset," in *Binaural and Spatial Hearing in Real and Virtual Environments*, edited by R. H. Gilkey and T. B. Anderson (Erlbaum, Hillsdale, NJ).

Hafter, E. R., and Dye, R. H. (**1983**). "Detection of interaural differences of time in trains of high-frequency clicks as a function of the interclick interval and number," J. Acoust. Soc. Am. **73**, 644–651.

Hartmann, W. M. (**1983**). "Localization of sound in rooms," J. Acoust. Soc. Am. **74**, 1380–1391.

Hartmann, W. M., and Rakerd, B. (**1989**). "Localization of sound in rooms IV: The Franssen effect," J. Acoust. Soc. Am. **86**, 1366–73.

Hartung, K., and Trahiotis, C. (**2001**). "Peripheral auditory processing and investigations of the "precedence effect" which utilize successive transient stimuli," J. Acoust. Soc. Am. **110**, 1505–13.

Kunov, H., and Abel, S. M. (**1981**). "Effects of rise-decay time on the lateralization of interaurally delayed 1-kHz tones," J. Acoust. Soc. Am. **69**, 769–773.

Lindemann, W. (**1986a**). "Extension of a binaural cross-correlation model by contralateral inhibition. I. Simulation of lateralization for stationary signals," J. Acoust. Soc. Am. **80**, 1608–1622.

Lindemann, W. (**1986b**). "Extension of a binaural cross-correlation model by contralateral inhibition. II. The law of the first wave front," J. Acoust. Soc. Am. **80**, 1623–1630.

Litovsky, R. Y., Colburn, H. S., Yost, W. A., and Guzman, S. J. (**1999**). "The precedence effect," J. Acoust. Soc. Am. **106**, 1633–1654.

Litovsky, R. Y., and Shinn-Cunningham, B. G. (**2001**). "Investigation of the relationship among three common measures of precedence: Fusion, localization dominance, and discrimination suppression," J. Acoust. Soc. Am. **109**, 346–358.

Rakerd, B., and Hartmann, W. M. (**1985**). "Localization of sound in rooms II: The effects of a single reflecting surface," J. Acoust. Soc. Am. **78**, 524–533.

Rakerd, B., and Hartmann, W. M. (**1986**). "Localization of sound in rooms III: Onset and duration effects," J. Acoust. Soc. Am. **80**, 1695–1706.

Saberi, K. (**1996**). "Observer weighting of interaural delays in filtered impulses," Percept. Psychophys. **58**, 1037–1046.

Saberi, K., and Perrott, D. R. (**1995**). "Lateralization of click-trains with opposing onset and ongoing interaural delays," Acustica **81**, 272–275.

Shinn-Cunningham, B. G., Zurek, P. M., and Durlach, N. I. (**1993**). "Adjustment and discrimination measurements of the precedence effect," J. Acoust. Soc. Am. **93**, 2923–2932.

Stern, R. M., Zeiberg, A. S., and Trahiotis, C. (**1988**). "Lateralization of complex binaural stimuli: A weighted-image model," J. Acoust. Soc. Am. **84**, 156–165.

Tollin, D. J., and Henning, G. B. (**1999**). "Some aspects of the lateralization of echoed sound in man. II. The role of stimulus spectrum," J. Acoust. Soc. Am. **105**, 838–49.

Wallach, H., Newman, E. B., and Rosenzweig, M. R. (**1949**). "The precedence effect in sound localization," Am. J. Psychol. **62**, 315–336.

Xia, J., Brughera, A., Colburn, H. S., and Shinn-Cunnigham, B. "Physiological and psychophysical modeling of the precedence effect," J. Assoc. Res. Otolaryngol. In press.

Yost, W. A., Mapes-Riordan, D., and Guzman, S. J. (**1997**). "The relationship between localization and the Franssen effect," J. Acoust. Soc. Am. **101**, 2994–2997.

Yost, W. A., and Soderquist, D. R. (**1984**). "The precedence effect: Revisited," J. Acoust. Soc. Am. **76**, 1377–1383.

Zurek, P. M. (**1980**). "The precedence effect and its possible role in the avoidance of interaural ambiguities," J. Acoust. Soc. Am. **67**, 952–964.

Zurek, P. M. (**1987**). "The precedence effect," in *Directional Hearing*, edited by W. A. Yost and G. Gourevitch (Springer-Verlag, New York), pp. 85–105.

Zurek, P. M., and Saberi, K. (**2003**). "Lateralization of two-transient stimuli," Percept. Psychophys. **65**, 95–106.