The effect of an additional reflection in a precedence effect experiment

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Studies on the precedence effect typically utilize a two-source paradigm, which is not realistic relative to real world situations where multiple reflections exist. A step closer to multiple-reflection situations was studied using a three-source paradigm. Discrimination of interaural time differences (ITDs) was measured for one-, two-, and three-source stimuli, using clicks presented over headphones. The ITD was varied in either the first, second, or the third source. The inter-source intervals ranged from 0–130 ms. A perceptual weighting model was extended to incorporate the three-source stimuli and used to interpret the data. The effect of adding a third source could mostly, but not entirely, be understood by the interaction of effects observed in the precedence effect with two sources. Specifically, for delays between 1 and 8 ms, the ITD information of prior sources was typically weighted more heavily than subsequent sources. For delays greater than 8 ms, subsequent sources were typically weighted slightly more heavily than prior sources. However, there were specific conditions that showed a more complex interaction between the sources. These findings suggest that the two-source paradigm provides a strong basis for understanding how the auditory system processes reflections in spatial hearing tasks.

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I. INTRODUCTION

In reverberant environments, a sound emitted from a source can propagate such that a person receives a direct sound and multiple reflections of that sound at the ears. In order for a person to determine the location of a sound source in a reverberant environment, the auditory system must extract the relevant location information from the direct sound and disregard conflicting information from the reflections. The various phenomena of the "precedence effect" indicate that the auditory system weights the localization information in direct sound or first wavefront more heavily than that in the later arriving reflections (see Blauert, 1997; Litovsky *et al.*, 1999 for reviews). The perceived locations of the sources change depending on the delay between the direct sound (also called the lead) and reflection (also called the lag) (Wallach *et al.*, 1949; Zurek, 1980; Gaskell, 1983; Yost and Soderquist, 1984; Saberi and Perrott, 1990; Shinn-Cunningham *et al.*, 1993; Tollin and Henning, 1998; Stellmack *et al.*, 1999; Litovsky and Shinn-Cunningham, 2001). When the lead-lag delay is very short (less than 1 ms), listeners perceive a single fused sound at a location somewhere between the actual locations of the lead and lag, referred to as "*summing localization*" (Warncke, 1941; Blauert, 1997). For delays greater than 1 ms but less than the threshold for hearing two separate sounds (i.e., an echo), the directional information from the lead dominates the perceived location of the fused auditory image, called "*localization dominance*." In the range of delays where localization dominance is observed, listeners have difficulty discriminating changes in the location of the lag, called "*lag discrimination suppression*" (Litovsky *et al.*, 1999; Litovsky and Shinn-Cunningham, 2001). As the delay is increased, changes in the directional information of the lag become easier to discriminate. In fact, for long delays (greater than 10 ms for clicks), the directional information in the lag may be easier than the lead to discriminate (Stellmack *et al.*, 1999) or localize (Litovsky and Godar, 2010). In these cases, Stellmack and colleagues postulated that listeners became confused about which source to report the location of, and thus often responded to the location of the most recently occurring source. This effect has been called "*temporal-order confusion*" (Stellmack *et al.*, 1999; Litovsky and Godar, 2010).

Besides the time delay between direct sound and reflections, which is related to the size of the room, other factors influence the ability to localize in rooms including the spectrum, reverberation time, and the attack of the stimulus onset (Hartmann, 1983; Rakerd and Hartmann, 1985, 1986; Hartmann and Rakerd, 1989). However, stimuli used in precedence studies are typically simplifications of realistic room acoustics because they use two sources, a lead and a lag, perhaps emitted from two loudspeakers in an anechoic room (e.g., Olive and Toole, 1989; Freyman *et al.*, 1991; Litovsky and Macmillan, 1994; Yang and Grantham, 1997; Rakerd *et al.*, 2000) or presented over headphones with interaural time differences (ITDs) that represent spatial cues of the lead and lag (e.g., Litovsky *et al.*, 1999; Litovsky and Shinn-Cunningham, 2001). Regardless of the stimulus

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presentation method, the vast majority of previous precedence studies have used only two sources.

The purpose of the present study was to expand the understanding of the precedence effect to three sources, or a direct sound and two reflections, thus moving precedence studies in the direction of more realistic listening environments where multiple reflections occur. It may be that for more than two sources there is a complex interaction of effects related to the precedence effect. A few studies have examined the effects of three or more sources with respect to the precedence effect. In one such study, Ebata *et al.* (1968) presented clicks from three sources over headphones. The first click had zero ITD; the second click was attenuated by 5 dB, delayed by 3 ms, and had an ITD to the left; the third click had an ITD to the right. The inter-source interval (ISI) between the first and third sources, the ITDs of the second and third sources, and the level of the third source relative to the first were varied. They found that the ISI necessary to change the perceived lateralization of the sound from the center to the right was larger with three clicks than with just two clicks, showing that the intermediate click affected the perception of the sound. They also found that longer ISIs were necessary to achieve detection threshold for sources that were more attenuated.

Another three-source precedence study was performed by Tollin and Henning (1999) who used a lateralization-discrimination paradigm. The stimuli were clicks with a 150-μs ITD in the second source and zero ITD in the first and third sources. They varied the ISI between 0.2 and 5 ms such that the time between sources one and two was the same as between sources two and three. They found that sources occurring within 2–3 ms of the direct sound provided lateralization information and were not substantially suppressed as occurs when there are only two sources.

Yost (2007) asked listeners whether they heard one or more than one sound in an experiment using single clicks or click trains presented from two or three loudspeakers at different locations in the horizontal plane. The ISI between sources one and two was 3 ms; the ISI between sources one and three was 6, 7.5, 9, 10.5, or 12 ms. Source two was attenuated by 0 or 6 dB; source three was attenuated by 0, 6, or 12 dB. The results showed that the proportion of trials where more than one sound was heard increased as the time between the first and last source increased, seemingly independent of the existence of an intermediate source and contrary to that found in Ebata *et al.* (1968) and Tollin and Henning (1999). The results also showed that the proportion of trials where more than one sound was heard decreased with increasing attenuation of the third source, which does appear to be consistent with Ebata *et al.* (1968).

Tan *et al.* (2000) presented speech stimuli over three loudspeakers placed at the midline and ±45° of the midline in a semi-anechoic room. The stimulus was first presented from the left loudspeaker, followed by presentation from the center loudspeaker, which lagged by 6, 10, or 20 ms compared to the left. The stimulus was also presented from the right loudspeaker and had an adjustable delay compared to the left loudspeaker. The task was to note the direction of perceived auditory images for delays of the right loudspeaker between 0 and 1 s. They found that listeners reported an extra auditory image when the delays between the center and right loudspeaker were similar. The image moved from left to right as the delay increased, consistent with the idea that summing localization occurred between the center and right sources. For delays of the right loudspeaker much longer than the center loudspeaker, an echo was heard.

Olive and Toole (1989) performed a number of experiments on the precedence effect using speech presented over a loudspeaker positioned at the midline and another 45° to the right of the midline, simulating a direct sound and reflection from a lateral wall, respectively. The task was to adjust the level of the simulated reflection until it was at detection threshold. In one experiment, they tested the effect of having a direct sound, a -3 dB reflection collocated with the direct sound, and a lateral reflection. They found that the detection threshold of the lateral reflection was lower if the collocated reflection was 1 ms after the direct sound compared to 20 ms after the direct sound. They also found that detection thresholds were relatively unaffected by the delay between the direct sound and the lateral reflection. Olive and Toole also performed experiments with a direct sound and lateral reflection in rooms that were slightly or moderately reverberant. Thus, the reflections from the room could interact with the direct sound and simulated reflection from the loudspeakers. Detection thresholds were not appreciably different between anechoic and reverberant rooms for time delays between the direct sound and simulated reflection up to 30 ms. For delays longer than 30 ms, detection thresholds were higher for increasing room reverberation. It was also found that a lateral reflection delayed 20 ms and -4 dB compared to the direct sound had little effect on the audibility of the other uncontrolled room reflections. Therefore, the late arriving room reflections appeared to matter despite the presence of the strong lateral reflection.

Bech (1998) simulated the time delays and amplitudes of the first 17 reflections of a sound presented by a loudspeaker in a small room. For broadband noise or speech, he found the detection threshold of a spatial change in the sound for reflections 1, 5, 9, 13, and 17 using a method of adjustment. Results showed that only reflection 1 (the first-order floor reflection) and energy above 2 kHz contributed to the spatial aspects of the sound field. This result is not necessarily contrary to Olive and Toole (1989) who found effects at delays longer than the last reflection used in this study, which was only 15 ms after the direct sound.

In summary, precedence studies with multiple reflections show that the intermediate source(s) may contribute to the sound perception. However, these studies tested a limited number of ISIs and different methods were used, which yielded differing opinions on the importance of the intermediate source(s).

Possibly related to the idea of multiple sources in precedence experiments are those that use click or noise-burst trains with fixed ITDs as would come from a single source. It has been shown that for trains with short (less than 10 ms) and constant ISIs, the localization information in the onset is weighted more heavily when presented over headphones (Hafter and Dye, 1983; Hafter *et al.*, 1983; Brown and Stecker, 2010) and (for the most part) when presented over loudspeakers (Stecker and Hafter, 2002, 2009). This onset dominance seems similar to the localization dominance in precedence studies as noted by Tollin and Henning (1998). Onset dominance is reduced if the ISIs are not constant (Hafter and Buell, 1990; Stecker and Hafter, 2002; Goupell *et al.*, 2009; Brown and Stecker, 2011), if the train is interrupted by another stimulus (Hafter and Buell, 1990), or if the train uses fresh noise tokens in each burst (Freyman *et al.*, 2010). This may be in turn related to the effects known as "buildup" and "breakdown" of precedence (Clifton and Freyman, 1989), which have been described under conditions using click trains that are presented from two locations. The buildup effect demonstrates that after several repetitions of the two sources, the lagging source perceptually becomes less salient or "fades away" and is difficult to localize. The breakdown of the buildup effect occurs if certain features of the stimuli change, such as when the positions of the two sources are interchanged; in that case, the buildup disappears and the lag becomes audible and localizable again (Clifton, 1987). Note that the types of experiments with trains of clicks or noise bursts that come from one or two sources are different from the three-source experiments described above because it is unlikely that reflections in a room would come from the same direction as the direct sound or a reflection. However, one study was performed to understand the breakdown of precedence using more than two sources.

Yost and Guzman (1996) measured the breakdown of precedence for a train of clicks that were presented from two or three loudspeakers. After ten repetitions of the clicks, the location of the source and second reflection were switched. For two sources separated by 12 ms, two sources were perceived. However, for three sources each separated by 6 ms, one source was perceived. Therefore, even though the first and third sources were separated by 12 ms (as in the two source case), the second source changed the perception from two sounds to one. This indicates that the number of reflections and ISI affects sound perception.

The present experiment was conducted to quantitatively compare the precedence effect using two and three sources in a more systematic fashion than previously performed. We independently varied the ISIs between three sources over a large range from 0–130 ms, extending the lag discrimination suppression paradigm of Litovsky and Shinn-Cunningham (2001) to include multiple reflections and long ISIs. Our goal was to understand how multiple reflections may change the scale at which summing localization, localization dominance, lag discrimination suppression, and temporal-order confusion occur. We also modified a perceptual weighting model introduced by Shinn-Cunningham *et al.* (1993) to summarize and understand the results.

II. PERCEPTUAL WEIGHTING MODEL

The perceptual weighting model of Shinn-Cunningham *et al.* (1993) assumes that a lead-lag pair produces a single fused image at a particular lateral position, α, found by a weighted average

$$\alpha = c_1\tau_1 + c_2\tau_2 + \eta = c_1\tau_1 + (1 - c_1)\tau_2 + \eta, \qquad (1)$$

where c_1 is the weight of the first source, c_2 is the weight of the second source, τ_1 is the ITD in the lead, τ_2 is the ITD in the lag, and η is a zero-mean Gaussian-distributed random variable that represents trial-by-trial noise. Note that both weights are bounded by 0 and 1 and are constrained such that

$$c_1 + c_2 = 1. \qquad (2)$$

This model has been used to quantify the data in many studies (Litovsky and Macmillan, 1994; Chiang and Freyman, 1998; Litovsky and Shinn-Cunningham, 2001; Akeroyd and Guy, 2011). These studies generally find that c_1 is near a value of 1 for ISIs of a few milliseconds, meaning that the location of the lead source almost completely dominates the perception of the sound location; however, factors like hearing loss may reduce the weight of the lead (Akeroyd and Guy, 2011).

In Shinn-Cunningham *et al.* (1993), a derivation of the perceptual weights was included for a discrimination experiment, where the the magnitude of the ITD was adaptively varied and the target source had an ITD that changed from positive to negative, or vice versa [Eqs. (12)–(18)]. Although the final weight was in terms of the measured just-noticeable differences, it is possible to reformulate the weight in terms the percentage of correct responses (PC) by using Eq. (15) of Shinn-Cunningham *et al.* if fixed ITDs are used in the experimental design. This reformulation yields

$$c_1 = \frac{\Phi^{-1}(PC_1)}{\Phi^{-1}(PC_1) + \Phi^{-1}(PC_2)}, \qquad (3)$$

where PC_1 is the percentage of correct responses when the target source is the lead, PC_2 is the percentage of correct responses when the target source is the lag, and $\Phi^{-1}(x)$ is the inverse cumulative normal function with zero mean and unit variance. The perceptual weight for the second source, c_2, can be found by the constraint in Eq. (2).

We extended the weighting analysis to three sources. We assumed that the ITDs in each source contributed to the final perceived location such that

$$\alpha = c_1\tau_1 + c_2\tau_2 + c_3\tau_3 + \eta, \qquad (4)$$

where c_i is the weight and τ_i is the ITD of the ith source. The weights are constrained such that

$$c_1 + c_2 + c_3 = 1. \qquad (5)$$

In our discrimination experiment, two non-target sources are at fixed ITDs and the target source to be discriminated has an ITD that changes sign (see Secs. III B and III C). Thus, the weights can be derived similarly to the two-source case because the non-target sources can be considered as a composite sound that changes the weight of the target source.

Solving the system of equations relating PC and ITD for three separate sources and using Eq. (5), the weights become

$$c_i = \frac{\Phi^{-1}(PC_i)}{\sum_{j=1}^{3} \Phi^{-1}(PC_j)}, \tag{6}$$

where $i = 1$, 2, or 3 enumerates the temporal position of the target source. Further extension to more sources would be possible as long as only the target source changes ITD in the discrimination task while the non-target sources remain at fixed ITDs.

Note that the assumption made in Shinn-Cunningham *et al.* (1993) about the fusion of the sources into a single auditory image can be ignored for our purposes because we used a discrimination task. For example, we calculated weights for long ISIs, well beyond the echo threshold. This becomes important for ISIs in which increased discrimination performance of the second or third source might be observed, which could be related to temporal-order confusion.

The weighting method described here is essentially a constrained linear regression and is similar to an observer weighting analysis (e.g., Lutfi, 1995). However, it would be necessary to include a random independent variable in the experimental design, such as random ITDs for the sources in each trial, to utilize observer weighting.

III. EXPERIMENT

A. Listeners and equipment

Five listeners between 21 and 28 years old were tested in this experiment. All five listeners had pure tone thresholds within 20 dB of audiometrically normal hearing at octave interval frequencies between 250 and 8000 Hz. Also, for each listener, the thresholds between the two ears differed by less than 10 dB at any tested frequency. Listeners provided informed consent for their participation in the study and were paid an hourly wage. They were naïve to the psychoacoustical task performed.

Stimuli were generated on a personal computer in MATLAB (the Mathworks). A Tucker–Davis Technologies (TDT) System 3 (RP2.1 and HB7, Florida) delivered the stimuli to headphones (HD580, Sennheiser, Germany). The tests were performed in a double-walled sound booth (IAC, New York).

B. Stimuli

Groups of one, two, or three wideband binaural click pairs were used as stimuli in the experiment. The pairs are referred to henceforth as "sources." Each click was filtered by a tenth-order bandpass Butterworth filter with corner frequencies of 500 and 18 000 Hz.

Each click started as a 20-μs rectangular pulse, a single sample for a 50-kHz sampling rate. The stimuli were resampled before presentation using the TDT sampling rate of 48.848 kHz. A train of these clicks presented at 4 Hz had an A-weighted sound pressure level of 60 dB.

The sources had an ITD applied using a spherical head model (Woodworth and Schlosberg, 1954), but zero ILD was applied. The spherical head model produced ITDs for different angles of incidence such that

$$ITD = \frac{d}{2} \cdot \frac{\theta + \sin(\theta)}{v}, \tag{7}$$

where $d = 0.18$ m is a typical diameter of a human head, θ is the angle of incidence in radians, and $v = 343$ m/s is the speed of sound. Sources in the model were at $-90°$, $-45°$, $+45°$, or $+90°$ with respect to the midline. After rounding due to the digital sampling of the signals, this yielded ITDs of -680, -400, $+400$, and $+680$ μs, respectively.

For the groups of two or three sources, the intervals between successive sources were varied systematically and intended to simulate delays between the lead and lags. An example of a three-source stimulus is shown in Fig. 1. The ISI between sources 1 and 2 is denoted by δ_{12} and between sources 2 and 3 by δ_{23}. Note that the ISIs were measured from the zero-ITD position (dashed vertical lines in Fig. 1) of each source. For the two-source conditions, the values of δ_{12} were 0, 1, 2, 4, 8, 16, 32, 65, and 130 ms. For the three-source conditions, δ_{12} and δ_{23} were systematically varied with similar values as was done for the two-source conditions, although there were some omissions for the longest ISIs. A list of experimental conditions can be seen in Table I.

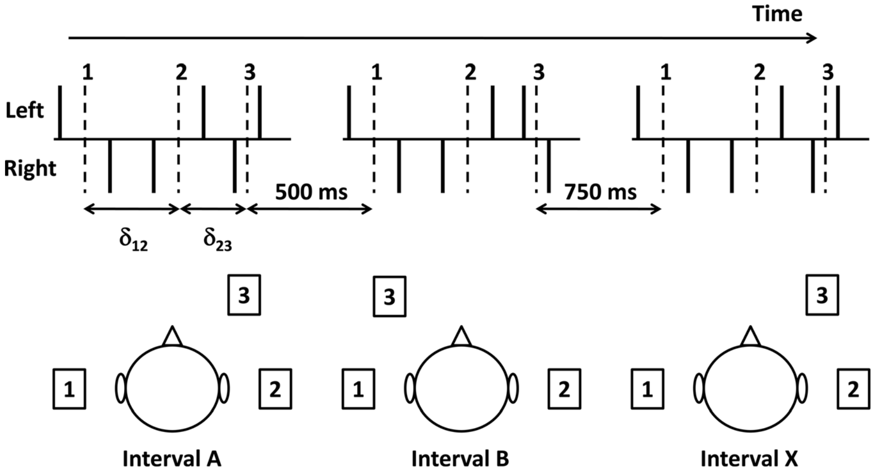


FIG. 1. Example of a three-source stimulus in the ABX task. At the top, the temporal order of the clicks (shown as vertical solid lines) is shown for the left ear (above the horizontal lines) and the right ear (below the horizontal lines). The dashed vertical lines denote the zero-ITD position of each source. The ISIs are denoted δ_{12} and δ_{23}. In this example, source 1 is presented at $-90°$ (ITD $= -680$ μs) in all three intervals, source 2 is presented at $+90°$ (ITD $= +680$ μs) in all three intervals, and source 3 is presented at $+45°$ and $-45°$ (ITD $= +400$ and -400 μs) in intervals A and B, respectively. Source 3 is presented at $+45°$ (ITD $= +400$ μs) in interval X. Hence, the correct answer for the ABX task is that interval A is the same as interval X.

TABLE I. Experimental conditions.

Number of sources	Source number	Source ITD (μs)	ISI (ms)									
1	1	±400	none									
2	1	±400	δ_{12}	0	1	2	4	8	16	32	65	130
	2	−680										
	1	−680	δ_{12}	0	1	2	4	8	16	32	65	130
	2	±400										
3	1	±400	δ_{12}	0	1	2	4	8	16	32	—	—
	2	−680	δ_{23}	0	1	2	4	8	16	32	65	130
	3	+680										
	1	−680	δ_{12}	0	1	2	4	8	16	32	—	—
	2	±400	δ_{23}	0	1	2	4	8	16	32	65	130
	3	+680										
	1	−680	δ_{12}	0	1	2	4	8	16	32	—	—
	2	+680	δ_{23}	0	1	2	4	8	16	32	65	130
	3	±400										

C. Procedure

Listeners participated in a three-interval, two-alternative forced-choice ABX task (Litovsky and Shinn-Cunningham, 2001). Within a block, all trials and intervals in a trial had the same number of sources (one, two, or three). An example of a three-source trial can be seen in Fig. 1. The source to be discriminated across trials, called the target source, was presented with an ITD of −400 or + 400 μs. In the one-source conditions, only the target source was presented. In the two-source conditions, there was also a non-target source presented with an ITD of −680 μs. In the three-source conditions, there were non-target sources presented with an ITD of −680 or + 680 μs. The temporal position of the target source varied depending on the condition tested.

During each trial, the first (A) and second (B) intervals were separated by 500 ms, measured from the last source of interval A to the first source of interval B. On intervals A and B, one interval contained the target source with an ITD of −400 μs and the other + 400 μs; the order was randomly chosen in each trial. The third (X) interval occurred 750 ms after the last source in interval B and had a target source with an ITD of −400 or + 400 μs. The task of the listener was to pick the interval (A or B) that was similar to interval X.[1] Feedback was given after each trial. The task was designed to measure listeners' ability to extract directional information from any one of the sources on any condition; the ITDs of ±400 μs were selected to reduce interference from the non-target sources with ITDs of ±680 μs.

Listeners were initially trained on one-source discrimination, which is simply an ITD discrimination task, for 200 trials with correct answer feedback. Then listeners were tested on an additional 40 trials. After this, conditions were tested in a block format. Each block had 180 trials, the ISI(s) was (were) fixed, as were the temporal order of target and non-target sources. There were 18 two-source conditions (2 target source positions × 9 δ_{12} values), which were tested in a different random order for each listener. After completing the two-source conditions, 175 three-source conditions (see Table I) were tested in a random order. After completion, the conditions were tested in reverse order for each listener, yielding 360 total trials for each condition.[2]

D. Results and discussion

1. One- and two-source conditions

The average PCs for the one- and two-source conditions are shown in Fig. 2, where chance performance is $PC = 50\%$. The average PC for the one-source condition (solid line) was greater than the average PC for all of the two-source conditions (symbols). Thus, regardless of the ISI, the ability of listeners to discriminate ITDs in either the lead or lag sources in the presence of another source was almost always reduced compared to the condition in which a single source was present. The PC for the one-source condition was not 100%, which was likely because of the lack of non-zero ILD in the stimulus [which may cause image blurring, see Hafter and Carrier (1972)], the smaller number of trials tested, and/or a training/familiarization/order effect.

For two sources with $\delta_{12} = 0$ ms, PC_1 and PC_2 were identical, which was expected because there was no physical distinction between the lead or lag sources. For $\delta_{12} = 1-8$ ms, PC_1 was higher than PC_2, which is consistent with the previously reported effect of localization dominance. For $\delta_{12} = 2-4$ ms, PC_2 was near chance performance, which shows the strong effect of lag discrimination suppression. For $\delta_{12} = 16-130$ ms, PC_1 was lower than PC_2. This reversal of the saliency of the directional information between the first and second sources can be explained by temporal-order confusion. As noted by Stellmack *et al.* (1999, p. 385) who tested similar conditions, "the subjective impressions of the listeners suggested the possibility that the [ITDs] of the source and echo were resolved, but that there was confusion as to the order in which the [ITDs] occurred." Thus, listeners likely heard distinct echoes at ISIs of 16 ms

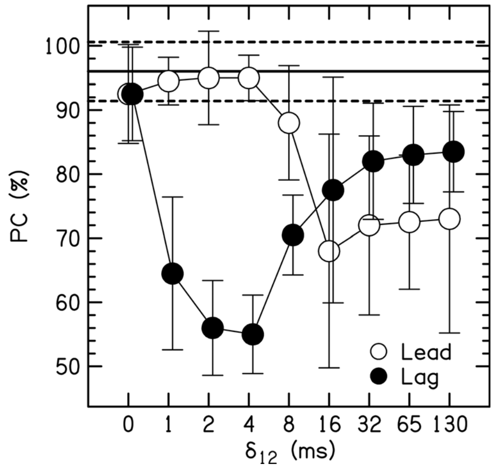


FIG. 2. One- and two-source discrimination data as a function of ISI. Open circles show the percentage of correct responses when the target source led (PC_1). Closed circles show when the target source lagged (PC_2). Each symbol represents the average PC over five listeners and the error bars show ±1 standard deviation. The solid line shows the average PC for one source; the dashed lines show ±1 standard deviation.

or greater and they preferentially, but not completely, tried to discriminate a change in position of the most recently occurring source, yielding better performance if the target source occurred later.

Note that the inter-listener variability was relatively larger for the longer ISIs, particularly at $\delta_{12} = 16$ ms, as shown by the larger error bars in Fig. 2. Large inter-listener variability for relatively longer ISIs was also seen in Litovsky and Shinn-Cunningham (2001). The large inter-listener variability may reflect how much temporal-order confusion affects an individual listener, which may have an underlying origin in a difference in echo thresholds between listeners.

The two-source conditions in this study were designed to be similar to those in Litovsky and Shinn-Cunningham (2001) in which a two-source precedence experiment was conducted using the same ABX paradigm. The difference between that study and the present one is that they used an adaptive procedure to measure ITD just-noticeable differences, whereas we measured *PC* for fixed ITDs, and there were small differences in the stimuli. Nonetheless, the trends in Fig. 2 agreed with those found in Litovsky and Shinn-Cunningham (2001). In addition to the conditions that were tested in Litovsky and Shinn-Cunningham (2001), we tested much longer ISIs to see if there was a recovery in a listener's ability to discriminate the ITD of the lead for longer ISIs. This never occurred, even for an ISI of 130 ms, which is possibly inconsistent with the findings of Stellmack *et al.* (1999) who found no difference in ITD discrimination performance between the lead and the lag sources if the ISI was 128 or 256 ms. Note that this only occurred in that study for conditions that used fixed ITDs for the target and non-target sources, and the non-target sources had zero ITD. On the other hand, ITD discrimination performance of the lead was below that of the lag if the non-target sources were randomly distributed about zero ITD, which would be consistent with our data. Thus, it may be that if the non-target sources have a non-zero ITD, the difference between PC_1 and PC_2 persists for long ISIs. Also, we did not test ISIs longer than 130 ms, which may have shown a full recovery of PC_1 to the level of PC_2.

The lead and lag weights for the average *PC* are shown in Fig. 3. The sources had an equal weight when there was no delay between the sources. The lead had a higher weight than the lag for ISIs of 1–8 ms. The lag had a higher weight than the lead for ISIs of 16 ms and longer. The lead had an increasing weight for ISIs of 1–4 ms, a decreasing weight for ISIs of 8–16 ms, and a constant weight for ISIs greater than 16 ms. The lag weight mirrored the lead weight exactly, which is necessitated by the constraint in Eq. (2). These weights are consistent with the weights calculated in Shinn-Cunningham *et al.* (1993) for the discrimination data from Zurek (1980), Gaskell (1983), and Saberi and Perrott (1990), which generally showed a high weight for the lead for ISIs less than 10 ms. For example, the lead weights were between 0.65 and 0.9 for an ISI of 1 ms in those studies, compared to $c_1 = 0.81$ in this study. The lead weights were between 0.8 and 1.0 for an ISI of 2 ms in those studies, compared to $c_1 = 0.92$ in this study. Thus, the approach taken here replicated previous findings and provides a baseline for understanding the three-source conditions in this study.

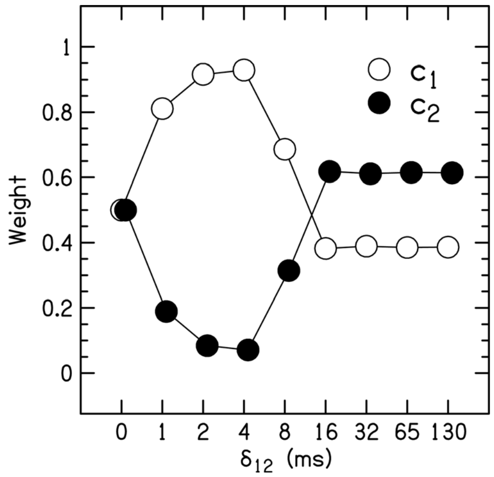


FIG. 3. Source weighting in the two-source conditions as a function of ISI.

2. Three-source conditions

The average *PC*s for the three-source conditions are shown in Fig. 4. Each row shows *PC* as a function of δ_{23} for a fixed value of δ_{12}. The left, center, and right columns show PC_1, PC_2, PC_3, respectively. Most panels show non-monotonic functions of δ_{23}. To help visualize the data, the source that yielded the largest *PC* value for each condition is plotted as a closed symbol in Fig. 4 and is also shown in Fig. 5. For example, consider the condition with $\delta_{12} = 2$ ms and $\delta_{23} = 4$ ms. Here $PC_1 = 92\%$, $PC_2 = 50\%$, and $PC_3 = 55\%$, so there is a "1" for this entry in Fig. 5. For the condition with two sources with the same maximum *PC* value, both are placed in the circle ($\delta_{12} = 8$ ms and $\delta_{23} = 1$ ms). Conditions where there was no physical distinction between the sources with approximately the maximum *PC* are plotted as a box with either two numbers or an X (to denote all three sources). The *PC*s within a few percent were considered equal because any difference was likely due to measurement noise. In Figs. 4 and 5, PC_1 was the largest of the three for most of the conditions tested, particularly for $\delta_{12} = 1$–8 ms and $\delta_{23} = 0$–8 ms, and a few conditions with $\delta_{12} = 16$–32 ms. PC_2 was mostly the largest of the three for $\delta_{12} = 16$–32 ms and $\delta_{23} = 1$–2 ms. PC_3 was mostly the largest of the three when $\delta_{23} \geq 16$ ms. These findings can be explained as follows:

(1) PC_1 was mostly the largest of the three when $\delta_{12} = 1$–8 ms and $\delta_{23} = 0$–8 ms; this pattern of results was similar to that observed in the two-source data where there was localization dominance of the first source (Fig. 2). For $\delta_{12} \geq 8$ ms or $\delta_{23} \geq 16$ ms, PC_1 decreased in a manner similar to those with long delays in the regime where temporal-order confusions typically occur.

(2) PC_2 was mostly the largest of the three when $\delta_{12} = 16-32$ ms and $\delta_{23} = 1-2$ ms. These values of δ_{12} would be in the regime of temporal-order confusion between sources 1 and 2. However, PC_2 quickly decreased as δ_{23} increased beyond 2 ms, presumably

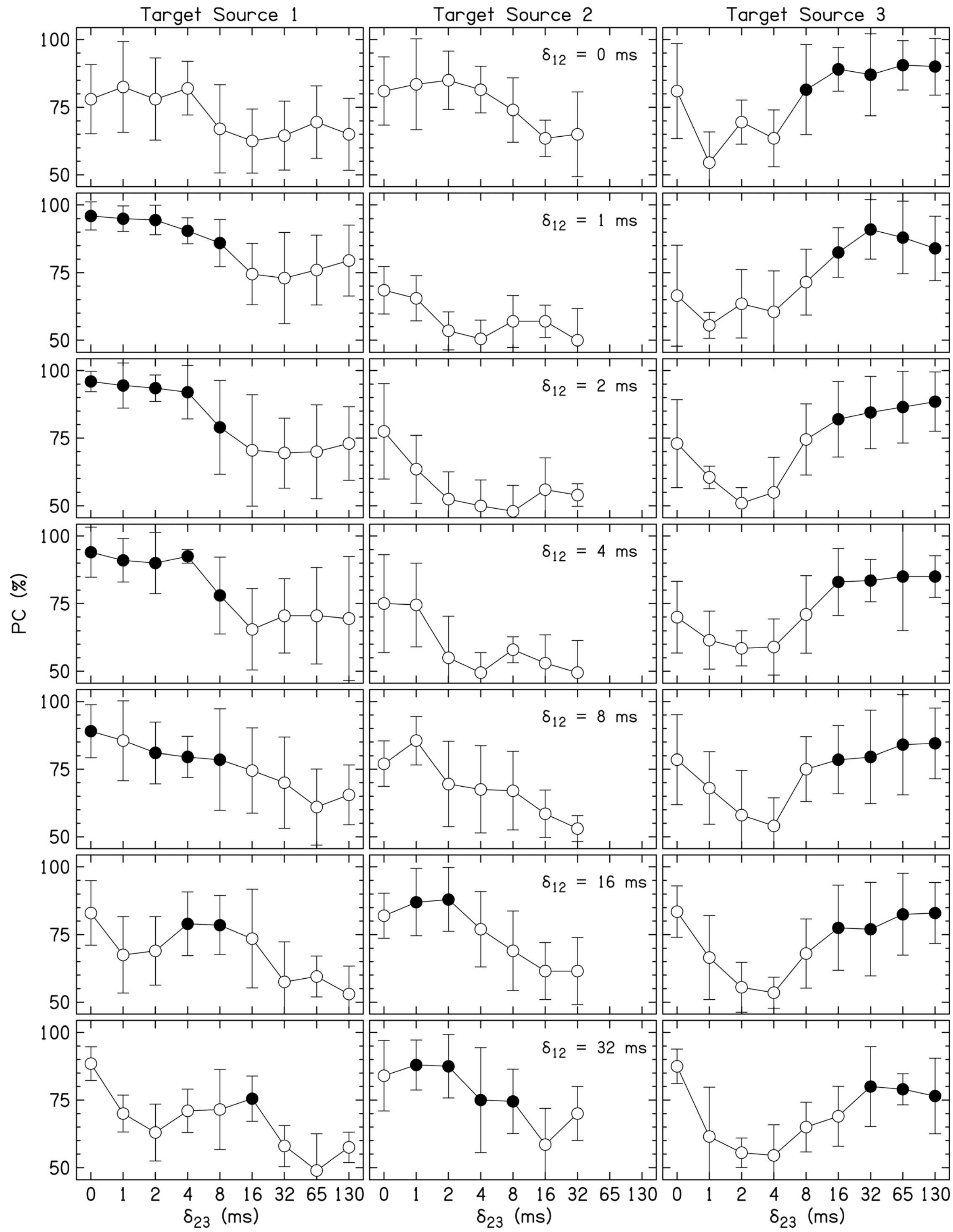
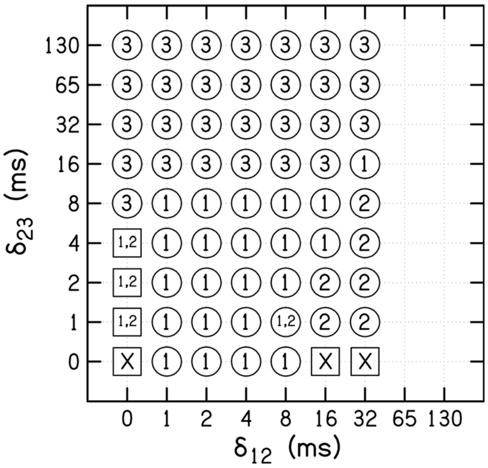


FIG. 4. Three-source discrimination data as a function of ISI δ_{23}. Each row shows a different ISI δ_{12}. Each column shows PC_1 (left), PC_2 (middle), or PC_3 (right). Each symbol represents the average and the error bars show ±1 standard deviation. Closed symbols show the target source with the maximum PC of the three sources for each condition.

where temporal-order confusion began to occur between source 2 and 3. The fact that PC_2 was smaller than PC_1 for $\delta_{12} = 16$ ms and $\delta_{23} = 4$–8 ms shows that there is a complex interaction of the three sources and it is not always possible to extrapolate precedence phenomena with two sources to those with three sources.

(3) PC_3 was mostly the largest of the three when $\delta_{23} \geq 16$ ms in the regime where temporal-order confusions occur.

Conditions where δ_{12} and/or $\delta_{23} = 0$ ms are special cases because the non-target sources can sum to create two diotic clicks separated by 680 μs. In Fig. 4, when all three sources were simultaneous ($\delta_{12} = \delta_{23} = 0$ ms), PC_1, PC_2, and PC_3 were nearly the same and about 80%, which was less than the near 90% performance for the two-source conditions in Fig. 2. For increasing δ_{12} and $\delta_{23} = 0$ ms, PC_1 increased and was greater than PC_2 and PC_3 until $\delta_{12} = 16$ ms. For these



δ_{23} (ms) \ δ_{12} (ms)	0	1	2	4	8	16	32	65	130
130	③	③	③	③	③	③	③		
65	③	③	③	③	③	③	③		
32	③	③	③	③	③	③	③		
16	③	③	③	③	③	③	①		
8	③	①	①	①	①	①	②		
4	[1,2]	①	①	①	①	①	②		
2	[1,2]	①	①	①	①	②	②		
1	[1,2]	①	①	①	(1,2)	②	②		
0	☒	①	①	①	①	☒	☒		

FIG. 5. Grid of conditions. The number in each circle corresponds to the source that produced the maximum *PC* for that condition. Circles with "1,2" represent equal *PC*s between sources 1 and 2 at that condition. Squares represent ambiguous conditions (δ_{12} and/or δ_{23} was zero) where there would be no physical difference in sources with the maximum *PC*. Squares with an "X" represent conditions where all three sources produced nearly equal *PC*s. Squares with "1,2" represent conditions that sources 1 and 2 had nearly equal *PC* that were much larger than source 3.

conditions, PC_1 in the three-source data was nearly equal to that measured in the two-source data in Fig. 2. In Fig. 4, for increasing δ_{23} and $\delta_{12} = 0$ ms, PC_1 and PC_2 were nearly equal for all values of δ_{23} and were greater than PC_3 until $\delta_{23} \geq 8$ ms. This trend is similar to that shown in Fig. 2 where there was only one lead source. However, one difference was that PC_1 and PC_2 were smaller for these conditions for two lead sources in Fig. 4 compared to PC_1 for conditions with one source in Fig. 2. To interpret these data generally, two sources that occur simultaneously and produce click pairs with zero ITD reduced the magnitude of the localization dominance and lag discrimination suppression in the three-source conditions, while also shortening the range of ISIs that these effects occur compared to the two-source conditions.

We calculated the perceptual weights for the average three-source *PC*s to better observe the relative performance between sources for each condition. The perceptual weights are shown in Fig. 6 for ISIs up to 32 ms with each source weight plotted in a different panel. Larger values of δ_{12} and δ_{23} could not be included because some ISIs greater than 32 ms were not tested. The left panel of Fig. 6 shows the perceptual weight for source 1, c_1. The highest weight occurred for $\delta_{12} = 2$ ms and $\delta_{23} = 2$–4 ms, which had values of $c_1 > 0.9$. Note that the highest weight also occurred for $\delta_{12} = 2$ ms in the two-source conditions in Fig. 3 and had a comparable magnitude. Larger values of δ_{12} and δ_{23} showed a decrease in c_1, with the lowest value of $c_1 = 0.13$. The average c_1 over all the conditions was 0.46.

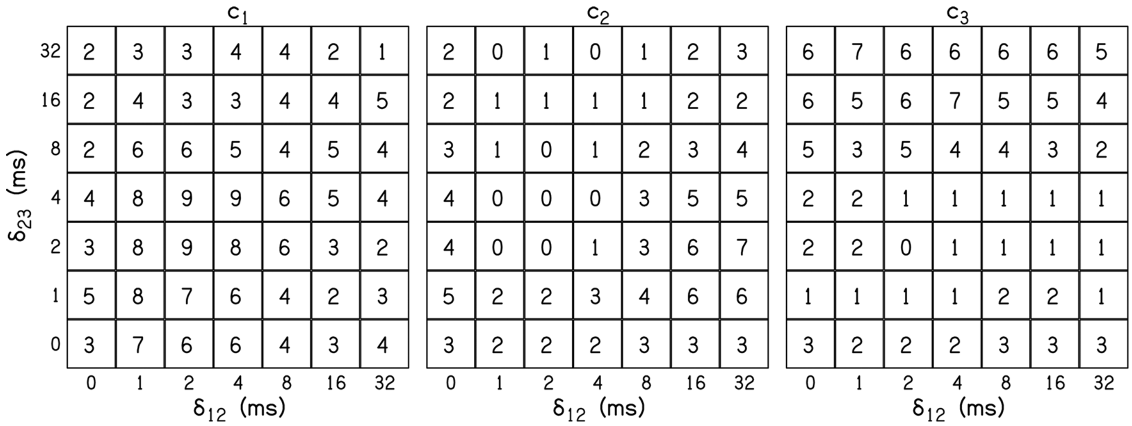
The middle panel of Fig. 6 shows the perceptual weight for source 2, c_2. There was essentially zero weight for source 2 for $\delta_{12} = 1$–4 ms and $\delta_{23} = 2$–32 ms. The lowest weight for the lag source also occurred for $\delta_{12} = 2$ ms in the two-source conditions in Fig. 3. The largest values of c_2 occurred for values of $\delta_{12} > 8$ ms. The single largest c_2 was 0.71, which occurred for $\delta_{12} = 32$ ms and $\delta_{23} = 2$ ms. The average c_2 over all the conditions was 0.24.

The right panel of Fig. 6 shows the perceptual weight for source 3, c_3. There was a relatively higher weight for source 3 when $\delta_{23} > 4$ ms, which was nearly independent of δ_{12}. The single largest c_3 was 0.69 for $\delta_{12} = 1$ ms and $\delta_{23} = 32$ ms. The average c_3 over all the conditions was 0.30.

To summarize the three-source weights, localization dominance mostly occurred for source 1 as expected (Fig. 6, left panel). For relatively longer delays between sources 1 and 2 ($\delta_{12} = 8$–32 ms), source 2 mostly showed localization dominance over source 3 (Fig. 6, middle panel). Lag discrimination suppression occurred for source 2 when δ_{12} was sufficiently small and for source 3 when δ_{23} was sufficiently small. There were areas of temporal-order confusion for source 2 when δ_{12} was sufficiently large and for source 3 when δ_{23} was sufficiently large. The interpretation of the perceptual weights in Fig. 6 was consistent with the *PC*s in Fig. 4.

IV. GENERAL DISCUSSION

This study shows that the precedence effect with three sources can, for the most part, be interpreted as the combination of effects commonly seen in the precedence effect



c_1

δ_{23} (ms) \ δ_{12} (ms)	0	1	2	4	8	16	32
32	2	3	3	4	4	2	1
16	2	4	3	3	4	4	5
8	2	6	6	5	4	5	4
4	4	8	9	9	6	5	4
2	3	8	9	8	6	3	2
1	5	8	7	6	4	2	3
0	3	7	6	6	4	3	4

c_2

δ_{23} (ms) \ δ_{12} (ms)	0	1	2	4	8	16	32
32	2	0	1	0	1	2	3
16	2	1	1	1	1	2	2
8	3	1	0	1	2	3	4
4	4	0	0	0	3	5	5
2	4	0	0	1	3	6	7
1	5	2	2	3	4	6	6
0	3	2	2	2	3	3	3

c_3

δ_{23} (ms) \ δ_{12} (ms)	0	1	2	4	8	16	32
32	6	7	6	6	6	6	5
16	6	5	6	7	5	5	4
8	5	3	5	4	4	3	2
4	2	2	1	1	1	1	1
2	2	2	0	1	1	1	1
1	1	1	1	1	2	2	1
0	3	2	2	2	3	3	3

FIG. 6. Source weighting in the three-source conditions as a function of the ISIs δ_{12} and δ_{23}. The left panel shows the weighting for source 1; the middle panel shows the weighting for source 2; the right panel shows the weighting for source 3. The number in the boxes reports the weight rounded to one significant digit for each condition with the "0." omitted for clarity (e.g., 0.74 is marked as "7").

with two sources, given the relatively good correspondence between the PCs (Figs. 2 and 4) and weights (Figs. 3 and 6). Namely, the effects can be understood in terms of summing localization, localization dominance, lag discrimination suppression, and temporal-order confusion. However, the magnitude and time scales of the effects using three sources can differ from what might be predicted from two sources. For example, by using the time scale of precedence with two sources, one would predict that PC_2 would be the largest of the three for $\delta_{12} = 16$ ms and $\delta_{23} = 4$ and 8 ms. Specifically, PC_2 should be greater than PC_1 because of temporal-order confusion, which occurs at ISIs of 16 ms or greater; PC_2 should be greater than PC_3 because of lag-discrimination suppression, which occurs at ISIs of 8 ms or smaller. In Fig. 5, contrary to expectation, PC_1 is the largest of the three for $\delta_{12} = 16$ ms and $\delta_{23} = 4$ ($PC_1 = 79$, $PC_2 = 77$, $PC_3 = 54\%$) or 8 ms ($PC_1 = 79$, $PC_2 = 69$, $PC_3 = 68\%$). Thus, when dealing with multiple reflections, in order to fully understand the salience of the directional cues from each source, measurement at the exact ISIs should be performed.

Some of the conditions we tested were included in prior studies. Tollin and Henning (1999) tested three-source stimuli whereby the first and third sources were diotic, and the second source had an ITD. They measured the percentage of correct lateralizations with ISIs ranging from 0.1–5 ms, such that the ISI was the same between the first and second, and second and third sources. They found that for ISIs of 1 ms or greater, listeners lateralized the sound to the correct side 70%–90% of the time, which is smaller than the near-perfect performance found when the ISI was 0 ms. In our data, when the first source was to the left and third source was to the right, $PC_2 = 81$, 66, 53, 50, 67, 62, and 70% ($c_2 = 0.35$, 0.18, 0.04, 0, 0.23, 0.17, and 0.33) for $\delta_{12} = \delta_{23} = 0$, 1, 2, 4, 8, 16, and 32 ms, respectively. Similar to Tollin and Henning, our listeners perceived the most salient change in position of source 2 for $\delta_{12} = \delta_{23} = 0$ ms ($PC_2 = 81\%$). However, contrary to Tollin and Henning, our listeners had great difficulty discriminating the ITD of source 2 for $\delta_{12} = \delta_{23} = 4$ and 8 ms ($PC_2 = 50\%$ and 67%, respectively). Perhaps the discrepancy between our data and those of Tollin and Henning is the use of non-target sources with non-zero ITDs or the use of a different task.

Yost (2007) presented three sources over loudspeakers with ISIs less than 12 ms and reported little effect of an intermediate source on the proportion of trials in which listeners heard more than one sound. Our discrimination data partially agree with theirs in that two lag sources have little influence on the lead source, thus likely to be perceived as a single sound, as long as the ISIs are shorter than 16 ms. However, for ISIs of 16 ms or greater, where temporal-order confusions typically occur, our data show the increasing importance and salience of the late arriving sources.

Although it is difficult to compare our discrimination results to studies that measured perceived lateralization of multiple sources (Ebata *et al.*, 1968; Tan *et al.*, 2000), there is agreement across studies in that the existence of an intermediate click in many cases does change the perception of the sound; this is confirmed from the non-zero weights of c_2 in Fig. 6, particularly at ISIs where δ_{12} is 0 ms or greater than 8 ms.

The present work has extended the understanding of the precedence effect to three separate sources. However, extrapolating these results to conditions where there are trains of clicks from a single source (e.g., Saberi, 1996) or two sources (e.g., Clifton and Freyman, 1989) may be difficult because of adaptation effects (Hafter and Dye, 1983). Other studies have shown the importance of adaptation in the auditory nerve, peripheral interactions between sources, and the ringing of the cochlear filters in understanding the precedence effect over time scales of 2 ms or less (Hartung and Trahiotis, 2001; Xia and Shinn-Cunningham, 2011). Hence, use of physiological models might be able to capture some of the features in our data set, particularly at ISIs of 10 ms or less. However, higher-level corrections to account for phenomena such as temporal-order confusion or pattern recognition (Freyman *et al.*, 2010) would be necessary for a complete explanation of the precedence effect.

V. SUMMARY

The precedence effect using three sources was systematically investigated over a large range of ISIs, which is an extension of the typical two-source precedence paradigm. The ability to discriminate a changing ITD of the target source was measured while the two other sources were held at other constant ITDs. The ability to detect spatial changes in the first source was for the most part the largest of the three sources if the other sources were delayed by less than 16 ms. The ability to detect spatial changes in the second source was for the most part the largest of the three sources if it occurred more than 8 ms after the first source, and the third source occurred less than 16 ms after the second source. The ability to detect spatial changes in the third source was for the most part the largest of the three sources if it occurred more than 8 ms after the second source. A fairly good correspondence of PC and the derived perceptual weights between the two and three source data was observed; however, it was not sufficient to simply extrapolate the time scales and magnitudes of the two-source phenomena to understand the three-source conditions in all cases.

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[1] Listeners could have used any consistent cue to perform the task, not just the spatial cue from the ITD. From our informal listening and discussions with listeners, we have a strong impression that the cues used in this experiment were spatial and that listeners were comparing perceived locations.

[2] One listener was missing the second block when the target was source 1, $\delta_{12} = 32$ ms and $\delta_{12} = 65$ ms. Since *PC* results are presented as the average over the listeners, this omission translates into 10% less trials for these two conditions.

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