Adjustment and discrimination measurements of the precedence effect

Barbara G. Shinn-Cunningham, Patrick M. Zurek, and Nathaniel I. Durlach
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 25 February 1992; revised 27 August 1992; accepted 12 January 1993)

A simple model to summarize the precedence effect is proposed that uses a single metric to quantify the relative dominance of the initial interaural delay over the trailing interaural delay in lateralization. This model is described and then used to relate new measurements of the precedence effect made with adjustment and discrimination paradigms. In the adjustment task, subjects matched the lateral position of an acoustic pointer to the position of a composite test stimulus made up of initial and trailing binaural noise bursts. In the discrimination procedure, subjects discriminated interaural time differences in a target noise burst in the presence of another burst either trailing or preceding the target. Experimental parameters were the delay between initial and trailing stimuli and the overall level of the stimulus. The model parameters (the metric c and the variability of lateral position judgments) were estimated from the results of the matching experiment and used to predict results of the discrimination task with good success. Finally, the observed values of the metric were compared to values derived from previous studies.

PACS numbers: 43.66.Qp, 43.66.Pn [HSC]

INTRODUCTION

The precedence effect refers to the phenomenon whereby greater emphasis is placed on the early-arriving components in localizing or lateralizing sounds composed of two or more components (for a review, see Zurek, 1987). Measurements of this effect have traditionally been of two basic types. In the first, adjustment methods are employed to match the position of a reference (or pointer) stimulus to that of a test stimulus by varying the parameters of either the reference or test stimulus (e.g., Wallach *et al.*, 1949; Yost and Soderquist, 1984). In some instances (for example, when subjects are asked to center the test stimulus) the reference stimulus may be absent. The second type of measurement requires discriminations to be made on characteristics of the early- or late-arriving components (Zurek, 1980; Gaskell, 1983; Saberi and Perrott, 1990). Comparisons of results on the precedence effect are hampered by these differences in methodology.

In the present study we propose and evaluate a simple model that, under certain conditions, summarizes adjustment and discrimination measures of the precedence effect with a single metric that reflects the relative contribution of the earlier component. First the model and its assumptions will be described, and then new adjustment and discrimination data will be presented to test those assumptions. Finally, values of the metric derived from the present experiment are compared to values derived from previously reported work.

I. MODEL

We consider only the case in which brief, broadband stimuli are presented over headphones. Each stimulus, henceforth referred to as a composite stimulus, is composed of two binaural bursts (called the initial and trailing bursts), as shown in Fig. 1. Interaural delays are positive when the right ear signal leads the left. Further, only the interaural delays of the component bursts (τ_1 and τ_2, respectively) are varied to affect lateral position.

The model assumes that each composite stimulus has a single lateral position that can be equated to a single effective interaural delay, α. The model proposes that α is a weighted, noise-corrupted average of τ_1 and τ_2:

$$\alpha = c\tau_1 + (1-c)\tau_2 + \eta, \tag{1}$$

where it is assumed that $0<c<1$ and that η is a zero-mean, Gaussian-distributed random variable that is independent from presentation to presentation. The standard deviation of η is denoted by σ. With such a model, a strong precedence effect is indicated by values of c near 1. If there were no precedence effect, and the perceived position depended equally on τ_1 and τ_2, the value of c would be 0.5. Equation (1), together with the constraint that c lies between 0 and 1, implies that the mean value of α falls within the bounds of τ_1 and τ_2, which, for these stimuli, is equivalent to assuming that the mean composite stimulus position falls between the positions at which the initial and trailing bursts would be heard if presented alone.

The basic assumption of the model is that the combined effects of the leading and trailing interaural delays can be represented by their weighted average. This assumption will be violated only if α falls outside of the interval $[\tau_1,\tau_2]$ bounded by the two stimulus delays, since a value for c between 0 and 1 can always be found to satisfy Eq. (1) when α falls between τ_1 and τ_2.

The model in Eq. (1) is presented in its simplest form, in which c and σ are written as constants, independent of stimulus parameters. While these quantities are expected to

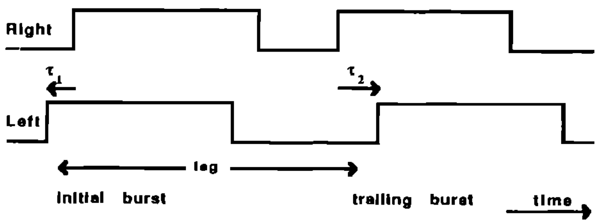

FIG. 1. Schematic diagram showing composite stimulus envelopes and temporal parameters. Lag is defined by the midpoints between left and right onsets. The interaural delay of the first burst is τ_1, and that of the second burst τ_2. Interaural delay is positive for right leading left, so that in this example, τ_1 is negative, τ_2 positive.

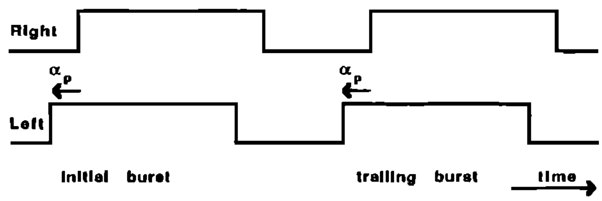

FIG. 2. Envelopes for one repetition of the pointer stimulus. The interaural delay α_p of both bursts is equal, and in this example is negative (left ear leads).

vary with such parameters as overall level and the lag between leading and trailing sounds, they might not vary with other parameters. For example, whether c varies with the interaural delays τ_1 and τ_2 is a matter of theoretical interest (Lindemann, 1986a, b). As an overall test of the model's ability to relate results from different procedures, adjustment and discrimination measurements of the precedence effect will be made and analyzed.

II. METHODS

All experiments were performed using TDH-39 headphones mounted in circumaural GS001 cushions. Subjects were seated in a soundproof room and presented with composite stimuli composed of white noise. The bursts were presented with a lag between their average onsets (see Fig. 1). There were no interaural level differences and no interburst level differences. The noise bursts were 1 ms in length and were constructed with a rectangular time window.

To construct the stimulus for one interval, a random white noise sample was selected. This sample was used to generate both initial and trailing binaural bursts, and thus was replicated four times (once for each ear, for each burst). The two bursts were coherent, and differed from each other only in interaural delay (if at all). These two bursts were combined with some interburst delay (the lag) to generate the final binaural stimulus.

A VAX 11/750 was used to run the experiments and to generate the white noise waveforms. Stimuli were presented via 16-bit D/A converters at an 80-kHz sampling rate.

Four subjects participated in the experiments. All had hearing within the normal range and were between 23 and 29 years of age. Experience levels varied: subjects BGSC, GO, and PC had been involved in binaural hearing research for up to 2 years before these experiments were performed; subject RKC was a novice in auditory experiments. Initial tests were monitored to detect any learning trends. Results reported here were taken after performance stabilized.

Both adjustment and discrimination measurements were made at two noise levels (80 and 110 dB SPL), and at two lags (1 and 10 ms). These values of lag were chosen to provide conditions with a strong (1 ms) and a weak (10 ms) precedence effect. Note that, for the 1-ms lag conditions, initial and trailing bursts overlapped in one of the channels when τ_1 and τ_2 differed in sign. Also for the 1-ms conditions, since initial and trailing binaural bursts were constructed from identical white noise samples, binaural interactions may have occurred not only for these bursts separately, but between initial left-ear signal and trailing right-ear signal, and initial right-ear signal and trailing left-ear signal. These possible interactions are not taken into account in the present study. The 10-ms lag was sufficiently long that overlap did not occur.

A. Pointer adjustments

An acoustic pointer was used as a measure of perceived lateral position of the two-burst test stimuli. The subject's task was to match the position of the pointer to that of a test stimulus. Like the test stimulus, the pointer stimulus also had two bursts; however, both bursts had the same interaural delay, α_p (subscript p for pointer), which was under the subject's control (see Fig. 2). Given the assumptions of the model, the mean effective interaural delay $\bar{\alpha}$ of the pointer stimulus is equal to the interaural delay of its two component bursts, α_p. Thus, measurements of α_p give estimates of $\bar{\alpha}$ for the pointer stimuli, and since the pointer's lateral position matched that of the test, α_p also is an estimate of $\bar{\alpha}$ for the test stimuli. The bursts in both test and pointer stimuli were presented with the same lag and level.

Measurements were made for an array of initial and trailing interaural time delays τ_1 and τ_2 formed using all combinations of τ_1 and τ_2 from the set $(-500, -150, 0, +150, +500)$ μs. Thus, there were 25 combinations of initial and trailing delays. The five combinations for which $\tau_1 = \tau_2$ provided a measure of adjustment precision for each subject.

The experiment started by presenting the subject with a train of test stimuli. For each composite stimulus in the train, a new white noise sample was randomly selected. Thus, each repetition of the two-burst test stimulus had the same values of τ_1, τ_2, lag and level, but differed in fine structure from stimulus to stimulus. The repetition rate of the test stimulus was 2 per second.

While listening to the test train, the subject could press a key at will to switch to the pointer train, and vice versa. As with the test train, each composite stimulus in the pointer train used a different sample of noise. To reduce confusion between test and pointer trains, the repetition rate of the pointer train was slightly slower than that of the test train (2 per 1.5 s).

The initial interaural delay of the pointer stimulus was random, between -1000 and $1000\ \mu s$. Using the keyboard, the subject adjusted α_p so that the perceived lateral position of the pointer matched that of the test. The smallest possible interaural delay adjustment was $12.5\ \mu s$, corresponding to a one-sample displacement at the 80-kHz sampling rate.

After a satisfactory match was obtained, the subject signaled completion of the trial and proceeded to the next (τ_1,τ_2) combination. A run consisted of 25 trials, one for each (τ_1,τ_2) combination. The order of the 25 trials in a run was randomized. Within a run, the lag and level were held constant.

Each run for a single level and lag time was repeated three times. Thus, since there were four level/lag combinations, at least 12 runs of 25 trials each were performed by each subject. If the performance for one condition changed dramatically for a subject (from run to run), the same condition was repeated until stable performance was achieved. Such a change occurred for only one subject, on one condition. The order of the basic runs was randomized to reduce fatigue and learning effects.

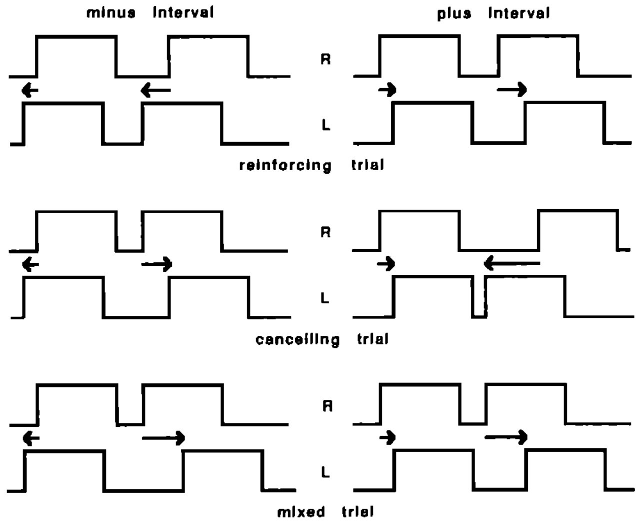

FIG. 3. Classification of trials for discrimination experiment with initial burst as target. In this example, the initial burst is the target and the trailing burst the interference. The plus interval has the target leading to the right by $50\ \mu s$.

B. Interaural delay discrimination

Discrimination measurements used a symmetric, two-interval, two-alternative, forced-choice paradigm. Each trial contained two intervals with each interval containing a two-burst stimulus. Either the initial or trailing burst played the role of "target" (the burst on which the discrimination task was to be performed), while the other burst served as the "interference." In one of the two intervals, the target burst had an interaural delay of $+50\ \mu s$ (leading to the right); in the other, $-50\ \mu s$ (leading to the left). Each interval was constructed from a different sample of white noise (although each burst in a stimulus was from the same sample). The interaural delay of the interference burst in each interval was a random variable distributed uniformly between -500 and $+500\ \mu s$ with resolution limited to $12.5\ \mu s$ by the 80-kHz sampling rate. Subjects were instructed to identify the interval (first or second) in which the target burst had an interaural delay of $-50\ \mu s$ (leading to the left). Values of each burst's interaural delay were stored by the computer, along with the correct response and subject response, for later analysis. Feedback was provided after every trial.

A run consisted of 50 trials. Four runs were performed for each combination of lag, level, and target choice (initial or trailing burst). Lags were 1 or 10 ms and levels were 80 or 110 dB SPL as in the pointer adjustment experiment. Since there were three parameters (lag, level, and choice of target burst), each of which could assume one of two values, there were eight different conditions to be tested. Each condition was repeated at least four times, yielding a minimum of 32 runs per subject and a minimum of 200 trials per data point. To test for learning effects, these 32 runs were performed as two sets of 16 runs. That is, all conditions were tested twice before any condition was repeated a third time.

Performance was measured by the percent correct response for all 200 trials, and was further broken down according to the relationship between the interference-burst interaural delay and the target-burst interaural delay. For each interval in a trial, the interference-burst interaural delay could either agree or disagree in sign with the target-burst interaural delay (see Fig. 3). Each trial was put into one of three categories depending on these signs. In a "reinforcing" trial, the interference delay had the same sign as the target delay in both intervals. In a "cancelling" trial, the sign of the interference delay disagreed with the sign of the target burst delay in both intervals. A "mixed" trial consisted of one interval in which the signs were the same and one in which they were opposing. Statistically, 25% of all trials were reinforcing, 25% were cancelling, and 50% were mixed.

III. RESULTS

A. Pointer adjustments

The results of pointer adjustments for the four combinations of lag and level are presented in Fig. 4(a)–(d). This figure shows the difference between the average pointer interaural delay $\bar{\alpha}_p$ and the target trailing burst interaural delay τ_2 as a function of $\tau_1-\tau_2$, the difference between the initial and trailing interaural delays for all combinations of τ_1 and τ_2. The data were plotted this way because, according to Eq. (1), $\bar{\alpha}-\tau_2=c(\tau_1-\tau_2)$. Since $\bar{\alpha}_p$ is an un-biased estimator of $\bar{\alpha}$, for any point on the graph the corresponding estimate of c is simply the slope of the line between that point and the origin. If c were constant over different (τ_1,τ_2) combinations, the data would fall along a straight line through the origin with slope c. In these plots, a strong precedence effect ($c\approx 1$ and therefore $\bar{\alpha}=\tau_1$) would be indicated by points falling along the diagonal line. The larger the deviation of the points from the diagonal, the weaker the precedence effect. Lines are shown for the values $c=0.25$, 0.50, 0.75, and 1.00.

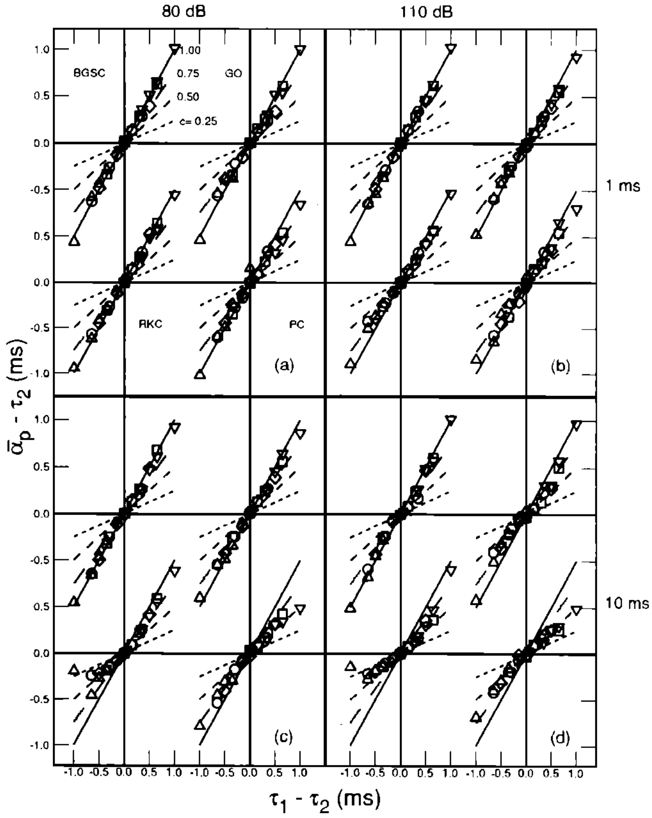

FIG. 4. Results of pointer adjustment experiment showing $\bar{\alpha}_p - \tau_2$ vs $\tau_1 - \tau_2$. The various straight lines show where points would fall for values of c=0.25, 0.50, 0.75, and 1.00. Each symbol corresponds to a different value of τ_1: △ = −500 μs, ○ = −150 μs, ◇ = +0 μs, □ = +150 μs, ▽ = +500 μs. Results for each subject are plotted separately in each frame: (clockwise from top left) BGSC, GO, PC, RKC. (a) Results for 80 dB, 1 ms. (b) Results for 110 dB, 1 ms. (c) Results for 80 dB, 10 ms. (d) Results for 110 dB, 10 ms.

The results in Fig. 4 show relatively little effect of the change in SPL from 80 to 110 dB. However, the effect of lag is strong. With a 1-ms lag, the data lie roughly on straight lines with slopes between 0.8 and 1.0. From Eq. (1), this is equivalent to c being approximately independent of the interaural delays τ_1 and τ_2, and with values in the range 0.8 to 1.0. The results with a lag of 10 ms show considerable inter-subject differences. Subject BGSC continues to show a linear relationship with a strong precedence effect (i.e., values of c near one). This is also true, but to a lesser extent, for subject GO. The results for PC show a more substantial deviation from a constant c, while RKC's data are strongly nonlinear and left-right asymmetric. Some of these adjustments correspond to values of c less than 0.5.

The average standard deviation for trials where $\tau_1 = \tau_2$ (a measure of the adjustment precision) varied from 20.0 μs (for subject RKC) to 60.8 μs (for subject PC). This variability did not appear to depend upon either lag or level, and was approximately equal to the average standard deviation across all matching trials for each subject and condition.

B. Interaural delay discrimination

Figure 5 shows graphs of performance on mixed and

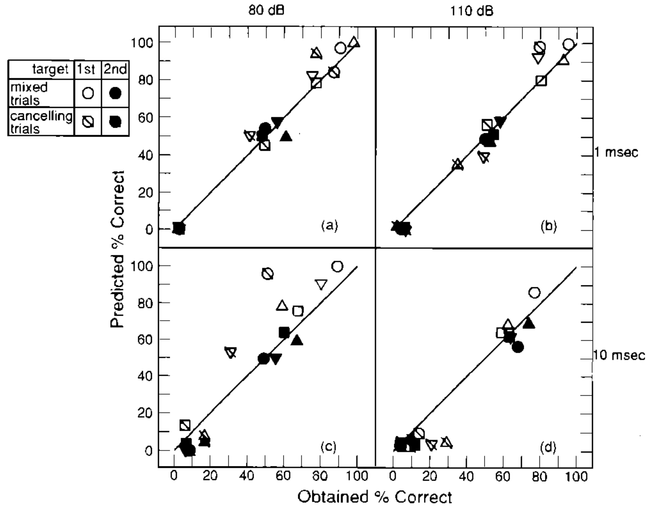

FIG. 5. Results of interaural delay discrimination, showing predicted percent correct versus obtained percent correct for mixed and canceling trials and initial and trailing burst targets. Each symbol corresponds to a different subject: ○ = BGSC, ▽ = GO, △ = RKC, □ = PC. Open symbols show results for initial burst interaural delay discrimination, filled symbols show results for trailing burst interaural delay discrimination. Plain symbols show results for mixed trials, slashed symbols show results for cancelling trials. (a) Results for 80 dB, 1 ms. (b) Results for 110 dB, 1 ms. (c) Results for 80 dB, 10 ms. (d) Results for 110 dB, 10 ms.

canceling trials for both initial and trailing bursts as targets. For brevity, Fig. 5 also includes predictions of performance that are derived and discussed in Sec. IV. Performance on reinforcing trials is not presented because, of the 32 points, 30 were greater than 90% correct and the remaining two greater than 85% correct. In these plots, the predicted performance (discussed below) is plotted against obtained performance, and the strength of the precedence effect is measured by the degree to which scores obtained on discriminating the initial burst (open symbols) are superior to scores obtained on discriminating the trailing burst (filled symbols). As with the results of the pointer adjustments, some subjects showed a stronger precedence effect than others. Also, in most cases the precedence effect is stronger for the shorter lag time. Some subjects show little precedence effect for longer lag times. BGSC, who showed the strongest precedence effect in the pointer adjustments, also shows the greatest difference in performance between initial and trailing burst discrimination.

IV. MODEL CALCULATIONS

A. Estimation of *c*

The least-square-error estimate $\bar{c}$ of the precedence-effect metric can be found using the results of the pointer experiment by

$$\bar{c} = (\bar{\alpha}_p - \tau_2)/(\tau_1 - \tau_2), \tag{2}$$

where $\bar{\alpha}_p$ is the mean pointer adjustment and τ_1 and τ_2 are the initial and trailing burst interaural delays for the given condition. Further, the expected error in the estimate $\bar{c}$ will depend on ρ, the root-mean-square error in the estimate of

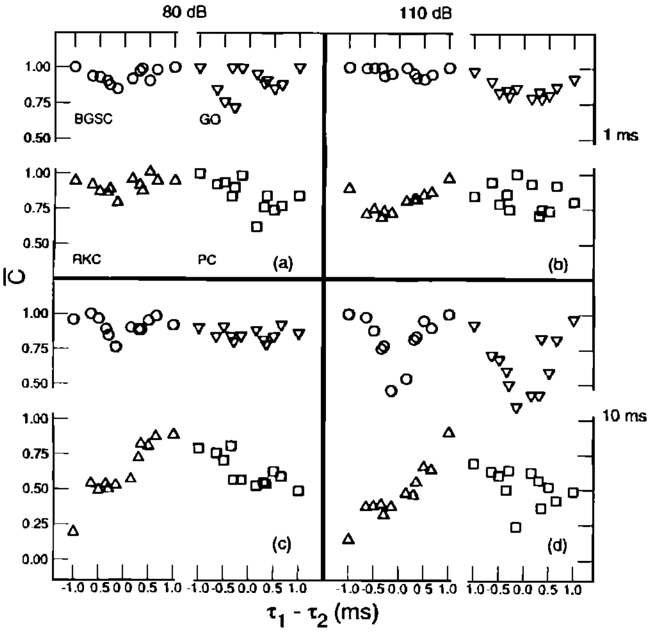

FIG. 6. Plot of $\bar{c}$ vs $\tau_1-\tau_2$. Estimates are calculated by averaging c estimates for each value of $\tau_1-\tau_2$. Dotted horizontal lines show where $c=0.50$ (initial and trailing interaural delays equally influential). Results for each subject are plotted separately in each frame: ○=BGSC, ▽=GO, △=RKC, □=PC. (a) Results for 80 dB, 1 ms. (b) Results for 110 dB, 1 ms. (c) Results for 80 dB, 10 ms. (d) Results for 110 dB, 10 ms.

$\bar{\alpha}_p$. Since ρ is the standard deviation of a mean of n observations, it will be related to the standard deviation σ of the observations as:

$$\rho=\sigma/\sqrt{n}. \tag{3}$$

If ϵ is the root-mean-square error of $\bar{c}$, ϵ can be estimated by

$$\epsilon=\sigma/\sqrt{n}(\tau_1-\tau_2). \tag{4}$$

B. Dependence of c on $\tau_1-\tau_2$

Figure 6 shows the estimated value of $\bar{c}$ as a function of $\tau_1-\tau_2$ for every subject and condition (organized as in Fig. 4). Since the model restricts $0<c<1$, if $\bar{c}$ exceeded 1.0, it was set to equal 1.0 exactly. The values of $\bar{c}$ never exceeded 1.06, and never were less than zero. For the 1-ms adjustment data for all subjects, the value of $\bar{c}$ lies between 0.7 and 1.0. Although there are variations in $\bar{c}$ with this time lag, they seem to be subject and/or level dependent.

The variations in $\bar{c}$ are stronger, but still idiosyncratic, with the 10-ms lag. For the 10-ms case, $\bar{c}$ is clearly symmetric around $\tau_1-\tau_2=0$ for BGSC and GO. At the higher level, the results for BGSC and GO show a decrease from $\bar{c}\approx 1$ (composite position depends only on initial burst interaural delay) to $\bar{c}\approx 0.5$ (composite position depends equally on initial burst interaural delay and trailing burst interaural delay) as $|(\tau_1-\tau_2)|$ approaches zero. At the lower level, the results for these same two subjects show a relatively constant value of $\bar{c}$ in the neighborhood of 0.85, similar to the results for the short time lag. For subject RKC, $\bar{c}$ increased with the signed difference $\tau_1-\tau_2$ (consistent with left-right asymmetric responses for those conditions). The results for RKC at both levels show a decrease from roughly $\bar{c}\approx 0.9$ (composite position depends mainly on initial burst i.t.d) to roughly $\bar{c}\approx 0.1$ (composite position depends mainly on trailing burst i.t.d) as $(\tau_1-\tau_2)$ decreases from 1 to -1 ms. For subject PC, whose responses showed the greatest variability, the results are constant within the expected variability of the calculated values of $\bar{c}$. Finally, the results for PC at the long lag time show a roughly constant $\bar{c}$ at approximately 0.5 at the higher level, and 0.6 at the lower level. The 10-ms results generally depend on level, on the interaural delays τ_1 and τ_2, and on the subject.

While not clear from Fig. 4, this way of plotting the matching results shows a small decrease in the strength of the precedence effect with increasing level. For the 10-ms lag, the average value of $\bar{c}$ across τ_1, τ_2 is larger for the 80 dB SPL data than for the 110 dB SPL data for every subject. This can be summarized by the average of $\bar{c}$ across subjects, which is 0.753 for a level of 80 dB SPL and 0.606 for a level of 110 dB SPL. For the 1-ms lag, this trend is less consistent; however, the average value of $\bar{c}$ across τ_1, τ_2 and subjects is still larger for the 80 dB SPL condition (0.900 for 80 dB SPL, 0.872 for 110 dB SPL).

C. Prediction of discrimination data

Let α_+ be the random variable describing the effective interaural delay of the composite image for the interval whose target burst has a time difference of $+50$ μs. Similarly, define α_- to be the effective interaural delay for the interval whose target burst has a time difference of -50 μs. If subjects base their responses on which of the two intervals had a more rightward lateral position, then the probability of a correct response equals the probability that α_+ is greater than α (the probability that the position of the interval whose target burst leads in the right ear is to the right of the lateral position of the interval whose target burst leads in the left ear). This response strategy would be the optimal strategy if the target interaural delays cannot be discriminated separately, and the only information about the target interaural delays is thus the lateral position of the composite burst.

According to the model, α_+ and α_- can be expressed as

$$\alpha_+=\bar{\alpha}(\tau_{1+},\tau_{2+})+\eta_+, \tag{5a}$$

$$\alpha_-=\bar{\alpha}(\tau_{1-},\tau_2)+\eta_-, \tag{5b}$$

where τ_{1+} and τ_{2+} are the interaural time differences in the interval whose target burst has a positive interaural delay, τ_{1-} and τ_2 are the interaural time differences in the interval whose target burst has a negative interaural delay, $\bar{\alpha}(\tau_1,\tau_2)$ is the expected value of the effective interaural delay α for the specified values of τ_1 and τ_2, and η_+ and η are independent, zero-mean Gaussian random variables with standard deviation σ. In these experiments, when the initial burst was the target, τ_{1+} was 50 μs and τ_{1-} was -50 μs; when the trailing burst was the target, τ_{2+} was 50

μs and τ_{2-} was -50 μs. Thus the probability of a correct response is given by

$$\Pr(\alpha_+ > \alpha_-) = \Pr(\bar{\alpha}(\tau_{1+},\tau_{2+}) - \bar{\alpha}(\tau_{1-},\tau_{2-}) > \eta_- - \eta_+). \quad (6)$$

This probability varies with the interaural delay of the interfering burst, which varied from trial to trial, giving each trial a different probability of correct response. Thus, the performance on a set of 50 trials corresponds to a sum of 50 Bernoulli random variables with different probabilities of success.

Since η_- and η_+ are zero-mean Gaussian random variables with variance σ^2, $\eta_- - \eta_+$ is a zero-mean gaussian random variable with variance $2\sigma^2$. Estimates of this variance were obtained from the match experiment results. Because, in the match experiment, the variance of the noise in α_p (and thus α) appears to depend only upon subject and condition, the noise in the target and pointer trains is assumed equal. In these experiments, if the positions of the repeated presentations of one train are averaged, the resultant noise in the effective interaural delay of that train is zero-mean Gaussian with variance decreased by an amount dependent on the amount of averaging. Subjects were asked to compare the positions of two such averages, so that the resultant noise could be thought of as the difference of two such Gaussian variables (doubling the variance). Since we were concerned with obtaining a rough estimate of the variance in the perceived position of a single presentation, and since the two above factors affect the variance observed in the match experiment results in different directions, it was assumed that the noise in the effective interaural delay of a single presentation was roughly equal to the noise found in repeated measures of α_p. Thus, σ is assumed to equal the experimental standard deviation of α_p.

For prediction of an estimate of the mean effective interaural delay α as a function of τ_1 and τ_2, it is necessary to have an estimate of $\bar{\alpha}(\tau_1,\tau_2)$ for every (τ_1,τ_2) used in the entire set of trials. While the matching experiment did find $\bar{\alpha}_p$ for a number of different values of (τ_1,τ_2), it did not estimate α for all combinations used in the discrimination task. Therefore, the needed values were found through interpolation of the values derived from the match experiment [see Shinn-Cunningham (1988) for the interpolation method].

The predictions of overall performance derived in the above manner are shown in Fig. 5, plotted against obtained scores. The predictions are reasonably accurate for all subjects and all conditions, although there is a tendency for predicted discrimination performance to be too high for discrimination on the first burst and too low for discrimination on the second burst. In other words, the matching experiment shows a slightly stronger precedence effect than the discrimination experiment.

D. Derivation of model parameter *c* from previous matching studies

Some previous studies of the precedence effect can be analyzed with the present model to find comparable values of the weighting metric *c*. This analysis is extended first to the results of Wallach *et al.* (1949). They presented 1-ms-long binaural click pairs separated by a 2-ms lag. For a given value of τ_2, the value of τ_1 was varied to find the pair of (τ_1,τ_2) values that gave rise to 50% "left" responses (relative to the subjective median plane of the subject). A simple interpretation of this task is that the mean effective interaural delay $\bar{\alpha}$ of the (τ_1,τ_2) stimulus is at the midline. Thus, for the measured values of (τ_1,τ_2)

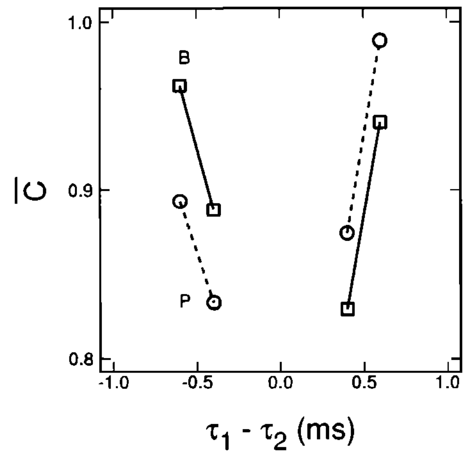

FIG. 7. Plot of $\bar{c}$ vs $\tau_1-\tau_2$ derived from Wallach *et al.* (1949). Results for two subjects are plotted together: □ = *B*, ○ = *P*.

$$\bar{\alpha} = c\tau_1 + (1-c)\tau_2 = 0, \quad (7)$$

which leads to

$$\bar{c} = \tau_2/(\tau_2 - \tau_1). \quad (8)$$

Figure 7 shows the derived values of $\bar{c}$ for the two subjects in the study as a function of the difference $\tau_1-\tau_2$. As in some of the current data (in Fig. 6), the value of $\bar{c}$ increases with increasing $|\tau_1-\tau_2|$. The values of $\bar{c}$ range from approximately 0.85 for $|\tau_1-\tau_2| \approx 0.4$ ms to 0.95 for $|\tau_1-\tau_2| \approx 0.6$ ms.

The current model can also be used to analyze the results of Zurek (1980). He reported results of a matching experiment that employed a pointer stimulus composed of a single binaural burst pair with no interaural level differences and an interaural time difference controlled by the subjects. This was set to match the perceived lateral position of a target stimulus comprised of an initial noise with interaural delay $+\tau$ and a delayed copy of the same noise with interaural delay of $-\tau$. In these experiments, the target stimulus was made up of continuous, low-pass filtered noise (as contrasted to the current study, which employed wide band noise bursts of 1-ms duration). Using the above model, the corresponding average effective interaural delay $\bar{\alpha}$ of the target's perceived lateral position can be represented as

$$\bar{\alpha} = c\tau + (1-c)(-\tau), \quad (9)$$

which leads to

$$\bar{c} = (\bar{\alpha} + \tau)/2\tau. \quad (10)$$

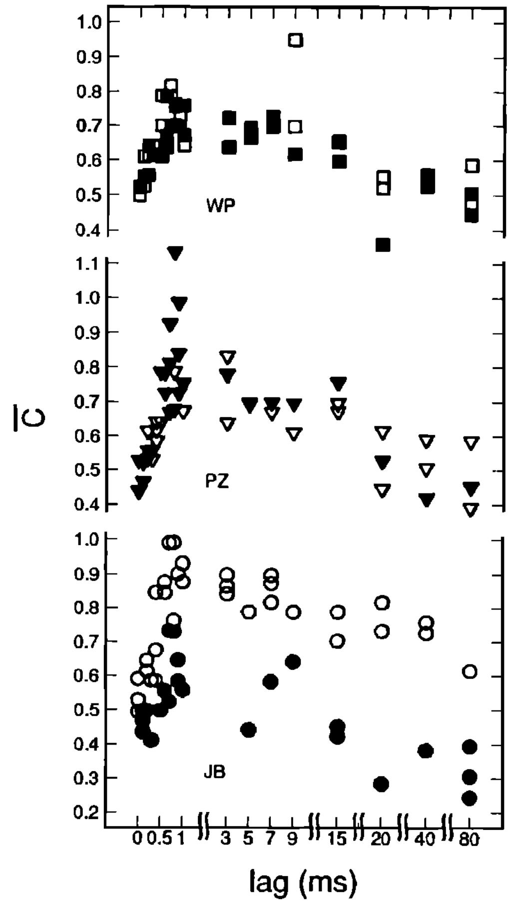

FIG. 8. Plot of $\bar{c}$ vs lag derived from Zurek (1980). Results for three subjects are plotted separately in each frame: □=WP, ○=JB, ∇=PZ. As in the original paper, open symbols represent trials in which the direct sound led to the left, filled symbols represent the symmetric case where the direct sound led to the right.

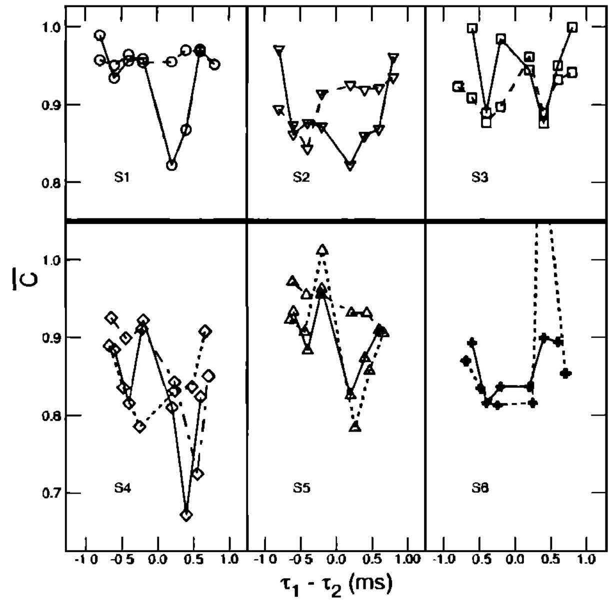

FIG. 9. Plot of $\bar{c}$ vs $\tau_1-\tau_2$ derived from Yost and Soderquist (1984). The top portion shows results of the midline reference task, and the bottom portion results of the off-midline results. In the top half of the figure, results for three subjects are plotted separately in each frame. Solid lines indicate results from a single-interval, absolute frame of reference task, dotted lines indicate results from a two-interval, 0-interaural delay reference sound task. In the bottom half of the figure, results for three subjects are plotted separately in each frame. Solid lines indicate a 0 μs interaural delay referent, dashed lines indicate a 200-μs interaural delay referent, dotted/dashed lines indicate a 400-μs interaural delay referent.

As in the current matching experiment, the interaural delay of the pointer gives an estimate of the average effective interaural delay $\bar{\alpha}$. Figure 8 shows the derived measures of $\bar{c}$ for Zurek's three subjects as a function of the lag between initial and trailing noises.

All three subjects show an increasingly strong precedence effect as the lag increases to approximately 1.0 ms. As the lag increases from 1.0 ms, the precedence effect lessens. These data are in rough agreement with the current results at lags of 1 and 10 ms. Of further note are the data of subject JB, whose responses became increasingly asymmetric with increasing lag. This is similar to the asymmetry seen in the current data of RKC.

Yost and Soderquist (1984) replicated the results of Wallach *et al.* (1949), and also asked subjects for judgements of left-right relative to a reference sound with a fixed interaural time difference, r. Stimuli consisted of 100-μs-long clicks separated by a lag of 1 ms. They first compared a single interval task (replication of the task of Wallach *et al.*, 1949) with a task in which subjects made left-right judgments relative to a reference with an interaural delay of 0 ms. For these experiments, Equation (10) holds, and the derived values of $\bar{c}$ are shown in the top portion of Fig. 9 as a function of the difference $\tau_1-\tau_2$. In the figure, the results for each of the three subjects in the study are presented separately. The solid line connects values of $\bar{c}$ from the single interval task and the dotted line the results from the comparable two-interval task. For subjects S1 and S2 in the one-interval task, $\bar{c}$ appears to increase with $|\tau_1-\tau_2|$. For subject S3 in both tasks, and for subjects S1 and S2 in the two-interval task, the values of $\bar{c}$ are more nearly constant between values of 0.9 and 1.0. The results with a target reference are comparable to the results from the current study: at a 1-ms lag $\bar{c}$ was approximately constant for different values of τ_1, τ_2 near a value of one. For the one interval task, the value of $\bar{c}$ resembles the current matching results at a longer lag.

Yost and Soderquist also examined the percentage of left versus right judgments relative to an off-midline reference with interaural delay r, and found pairs of (τ_1,τ_2) where the 50% left criterion was met. In these data, assuming that the 50% left judgments arise when $\bar{\alpha}=r$,

$$\bar{c}=(r-\tau_2)/(\tau_1-\tau_2). \tag{11}$$

The values of $\bar{c}$ as a function of $\tau_1-\tau_2$ for two-interval judgments with off-midline references are shown in the bottom half of Fig. 9 for the subjects employed in that portion of the study. Clear patterns are not discernable.

E. Derivation of model parameter *c* from previous discrimination studies

Zurek (1980) performed three-interval, forced-choice discrimination experiments to find the JND in interaural delay for both the initial burst and trailing burst. In this study, the burst to be discriminated (initial or trailing) had an interaural delay of $+\tau/2$ in the "odd" interval and $-\tau/2$ in the other intervals. The nontarget burst was diotic in all three intervals. The measured interaural delay JND was the target interaural delay (τ_{o1} for the first burst JND and τ_{o2} for the trailing burst JND) for which the $\Pr(c) = 67\%$. Let the effective interaural delay of the odd interval be denoted by α_{o1} for discrimination of initial burst interaural delay, and α_{o2} for discrimination of trailing burst interaural delay. Let the effective interaural delay of the other intervals be denoted by α_{s1} and α_{s2}. For trials with interaural delay at the threshold, the probability of a correct response for a single trial equalled the JND threshold probability, p.

For initial burst JND experiments, the effective interaural delays of the "odd" and "same" intervals can be given by:

$$\alpha_{o1} = c\tau_{o1}/2 + \eta_o \tag{12a}$$

$$\alpha_{s1} = -(c\tau_{o1})/2 + \eta_s, \tag{12b}$$

where η_o and η_s are samples of zero-mean, Gaussian noise with standard deviation σ. Assuming that the discrimination task is performed by comparing the lateral position of the odd interval to that of one of the other intervals, the model predicts:

$$p = \Phi(c\tau_{o1}/2\sigma), \tag{13}$$

where

$$\Phi(x) = \int_{-\infty}^{x} \frac{e^{-t^2/2}}{\sqrt{2\pi}}\, dt. \tag{14}$$

Thus

$$\Phi^{-1}(p) = c\tau_{o1}/2\sigma. \tag{15}$$

For experiments where the trailing burst JND is found, the effective interaural delay of the "odd" and "same" intervals is given by

$$\alpha_{o2} = (1-c)\tau_{o2}/2 + \eta_o, \tag{16a}$$

$$\alpha_{s2} = -(1-c)\tau_{o2}/2 + \eta_s, \tag{16b}$$

so that

$$p = \Phi\left(\frac{(1-c)\tau_{o2}}{2\sigma}\right), \tag{17}$$

which yields

$$\Phi^{-1}(p) = (1-c)\tau_{o2}/2\sigma. \tag{18}$$

Combining Eqs. (15) and (18) yields:

$$\bar{c} = \tau_{o2}/(\tau_{o1} + \tau_{o2}).$$

Similar analysis can be applied to the discrimination results of Gaskell (1983) and Saberi and Perrott (1990). The derived values of $\bar{c}$ from these three studies are plotted together in Fig. 10. In the study by Zurek, 1-ms-long noise bursts were used. These initial and trailing bursts were either identical (open squares and open circles) or statistically independent (filled squares and filled circles) for the two subjects in the study. The study by Gaskell (1983) used identical 20-μs-long clicks for initial and trailing bursts (upward triangles, from a single subject). Finally, the initial data[1] from the study of Saberi and Perrott (1990) used identical 40-μs-long clicks for initial and trailing bursts (downward triangles, results from average of four subjects). The value of $\bar{c}$ does not decrease as quickly with lag as in measures derived from matching results, so that the precedence effect appears to be somewhat more pronounced for these results at longer lags than in matching experiments. However, data from these three disparate studies show general agreement, and the tendency for c to decrease as lag increases is evident.

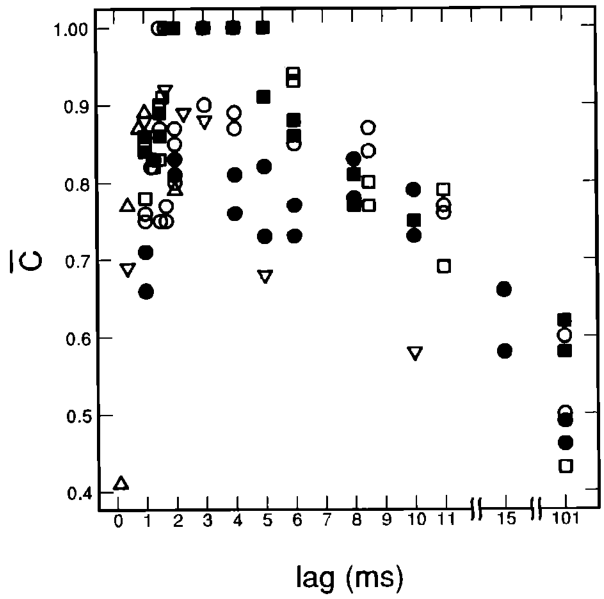

FIG. 10. Plot of $\bar{c}$ vs lag derived from various discrimination studies. Results from subject WP=□ and subject PZ=○ (Zurek, 1980). Gaskell (1983)=△. Saberi and Perrott (1990)=▽. Open symbols are from conditions where initial and trailing sounds are identical; filled symbols from studies where initial and trailing sounds are statistically independent.

V. DISCUSSION

The simple model presented here quantifies the strength of the precedence effect for the limited stimuli employed in this study (brief, wideband noise bursts with no interaural level differences) with a single metric (the value of c). For the stimuli in this study, this simple model is capable of relating measurements of lateral position with results from a discrimination experiment. However, it must be noted that the model is valid only for stimuli that have a single, distinct lateral position. When this condition is not met there is no longer a simple lateral position to match, nor is there a single effective interaural delay capable of summarizing the lateralization of the composite stimuli. In such cases, it is not surprising that subjects yield idiosyncratic responses (reflecting the presence of the second image).

From the present results, it appears that this condition was met for all subjects and conditions except for RKC with a 10-ms lag. RKC's pointer adjustments for this condition show an asymmetry that can be explained by assuming that he heard two images, one depending more strongly on the initial burst interaural delay and the other depending more strongly on the trailing burst interaural delay, and that he always adjusted the pointer to the rightmost image. It is noteworthy that the two postulated images must have been dependent upon both initial and trailing burst interaural delays to be consistent with the data, and that the predicted discrimination results were still relatively accurate for these cases.

Anecdotal reports by the subjects were consistent with these interpretations. Subject RKC reported multiple images with the 10-ms lag, which were most noticeable in the pointer adjustment experiment. This subject did *not*, however, consciously choose to match the right-most image; rather, he reported matching the image that seemed strongest in each trial.

For all remaining subjects and the conditions for which it appears that the single-image assumption is met (excluding RKC at the 10-ms lag), we can conclude that the single perceived position results from a weighted average of initial and trailing interaural delays. Further, the two bursts' interaural delays cannot be separately discriminated; rather, discrimination is based on a quantity that reflects the same weighting of initial and trailing interaural delays as measured positionally.

The precedence effect is strong for all subjects at a lag of 1 ms (as measured by $\bar{c}$ between 0.7 and 1.0). For three subjects (excluding RKC), the initial burst interaural delay is also more influential than the trailing burst interaural delay in the 10-ms data (i.e., $\bar{c}>0.5$).

This simple quantitative approach to examining the precedence effect can further be applied to previous studies. In these cases, the relative strength of the precedence effect (as reflected in the metric c) is comparable to the current results for various broadband stimuli when lateralization depends only upon interaural delay of initial and trailing sounds. Further, some interesting aspects of the current data can be found in these previous studies. Asymmetric lateralizations occur both in the current study (subject RKC) and in that of Zurek (1980; subject JB) as lag increases, and the sound image begins to break into two inter-dependent images. If subject JB is hypothesized to have the same response bias as that proposed for RKC (of responding preferentially to images on one side of the head in a matching paradigm), then his responses would exhibit an increasing asymmetry as lag increases and the two images break apart.

Of perhaps more interest is the trend seen in some of the data of Fig. 6, whereby $\bar{c}$ increases as $|\tau_1-\tau_2|$ increases. This dependence of $\bar{c}$ on $|\tau_1-\tau_2|$ occurs in the data from both Wallach *et al.* (1949) and some of the one interval results of Yost and Soderquist (1984). It appears that for conditions where the precedence effect is not "complete" (i.e., there is a measurable influence of τ_2 on lateralization), the "suppression" of the trailing sound lateralization is more effective when it is in a position distinct from that of the initial sound. This suppression pattern was commented on in Wallach *et al.* (1949), where it was evidenced by a non-monotonicity in the value of τ_1 required to offset values of τ_2 in a composite stimulus. They remarked that the effect was "More interesting, and quite unexpected..." (p. 332), and performed a follow up experiment that confirmed the finding.

Yost and Soderquist (1984) discuss differences between results from one- and two-interval tasks (Fig. 9) as resulting from imprecision. An alternative explanation may be due to differences in strategies employed by subjects in the two tasks. Previous discussion of the precedence effect (e.g., Lindemann, 1986a) have considered two possible lateralization criteria: one based on the position of a centroid in a neural spatial map of auditory location, and one based on the position of a maximum in a neural spatial map of auditory location. In the one-interval task, where a subject is asked to make judgments of left-right relative to some subjective scale, they may employ a strategy of judging location by the former strategy (matching a centroid). However, when asked to compare the location of the precedence-effect inducing interval to the location of a second interval which has a clearly defined location with a sharp maxima (that of the interval with a single interaural time delay), the maximum of the judged interval may be compared to the sharp, reference-interval's maximum. If it is assumed that the lateralization information of a second burst is suppressed incompletely, then the proposed neural map centroid will be displaced even when the suppression is sufficient to leave the maxima unaltered. In this analysis, the effect of an incomplete suppression of lateralization information from a trailing burst would be more evident with the one-interval task (which relies on the centroid) than with the two-interval task (which relies on the maxima). As the suppression weakens (e.g., with increasing lag), the maximum will be affected by the presence of the second burst as well. Thus, while the current matching results for a 1-ms lag do not show that c depends on $|\tau_1-\tau_2|$, this dependence is seen in the 10-ms lag results.

Most studies of the precedence effect have not examined the effects of varying τ_1 and τ_2, but rather have focused on the effect of lag, the spectrum of initial and trailing sounds, or other effects. Further, beyond the initial mention in Wallach *et al.* (1949), any nonmonotonic effects of varying τ_1 for a fixed τ_2 have been ignored. This possibility should be examined in more detail, as it has important implications for the underlying structure of the precedence effect.

In summary, this study suggests that pointer-adjustment and discrimination measurements of the precedence effect can be related via a simple, plausible model, and therefore reflect the same underlying phenomenon. The results lend credence to the use of discrimination measurements in characterizing a phenomenon that was originally described in terms of localization or lateralization. The consistency between position and discrimination measures also supports the view that the precedence effect stems from a loss of information about the trailing sound, and is not the result of a response bias towards the initial interaural delay in adjustment measurement.

ACKNOWLEDGMENTS

Work supported by Grant No. DC00100 from the National Institute on Deafness and Other Communication Disorders, and by fellowships to the first author from Bell Communications Research and MIT Lincoln Laboratory.

[1]The study by Saberi and Perrott (1990) found a change in performance with practice. The data plotted in Fig. 10 are taken from the initial results for their subjects, when the precedence effect was strongest.

Gaskell, H. (1983). "The precedence effect," Hear. Res. **11**, 277–303.

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 wavefront," J. Acoust. Soc. Am. **80**, 1623–1630.

Saberi, K., and Perrott, D. R. (1990). "Lateralization thresholds obtained under conditions in which the precedence effect is assumed to operate," J. Acoust. Soc. Am. **87**, 1732–1737.

Shinn-Cunningham, B. G. (1988). The precedence effect: An examination of some parameters affecting its strength. M. S. thesis, MIT, Cambridge, MA.

Wallach, H., Newman, E. B., and Rosenzweig, M. R. (1949). "The precedence effect in sound localization," Am. J. Psychol. **52**, 315–336.

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).