

# Sound localization precision under conditions of the precedence effect: Effects of azimuth and standard stimuli

Ruth Y. Litovsky<sup>a)</sup> and Neil A. Macmillan<sup>b)</sup>

Department of Psychology, University of Massachusetts, Amherst, Massachusetts 01003

(Received 9 October 1992; revised 6 December 1993; accepted 8 April 1994)

Minimum audible angles (MAAs) were estimated for single noise bursts, and for burst pairs that satisfied the conditions of the precedence effect (that is, produced fused images). In one burst-pair condition, the bursts to be discriminated differed in lead location; in the other, they differed in lag location. Sounds were presented over loudspeakers. MAAs were lowest for single bursts, slightly higher for lead discrimination, and much higher for lag discrimination. Presence of a standard reference burst had no reliable effect on performance. The data are interpreted using a model of Shinn-Cunningham *et al.* [J. Acoust. Soc. Am. **93**, 2923–2932 (1993)] in which discrimination of precedence-effect burst pairs is based on the lateral position of the auditory image, which is a weighted average of the positions of the leading and lagging bursts.

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

## INTRODUCTION

In a normal reverberant environment, sound arrives at the ears by more than one wavefront, that is, both directly and via echoes that are delayed in time. In the simplest such situation, two wavefronts separated by a brief delay arrive from different locations in space. For delays of a few ms, the echo is not perceived as a separate sound; rather, listeners experience one auditory image whose location is heavily dominated by the position of the earlier wavefront. This finding is called the “law of the first wavefront,” or the “precedence effect” (Wallach *et al.*, 1949; Zurek, 1987). It is well-known, however, that echoes have perceptual effects, even when they are not resolvable as separate auditory events. Listeners have little difficulty distinguishing trials on which the lagging wavefront is present from those on which it is absent (Blauert, 1983; Saberi and Perrott, 1990). Echoes add a richness and loudness to the sound (Blauert, 1983), and they do influence its perceived location (Hartmann, 1983; Rakerd and Hartmann, 1985, 1986; Perrott *et al.*, 1989). The location effect is the focus of the present study.

The relative contribution of the leading and lagging components to the perceived location of the fused sound has often been explored by simulating the precedence effect under headphone conditions. Each ear receives a pair of sounds, corresponding to direct and echoed wavefronts of a single auditory event. The two most important paradigms have been discrimination, in which the stimuli to be distinguished are designed to differ in the lateralization of the auditory image (Gaskell, 1983; Saberi and Perrott, 1990; Shinn-Cunningham *et al.*, 1993; Zurek, 1980); and adjustment, in which the position of a pointer stimulus is adjusted to match that of a target (Shinn-Cunningham *et al.*, 1993; Wallach *et al.*, 1949; Yost and Soderquist, 1984; Zurek, 1980). A common conclusion from such studies parallels the

free-field result: Lateralization of the compound (lead-lag) stimulus depends primarily but not solely on information from the first-arriving wavefront. For example, Zurek (1980) found in a pointing task that subjects matched the auditory image with an interaural delay similar to that of the leading stimulus, but somewhat displaced toward the lagging stimulus.

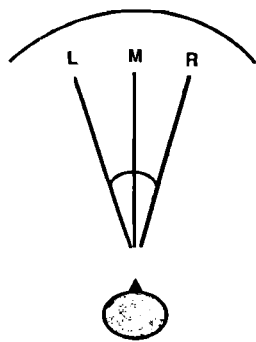
In the present study we measured the perceptual contribution of the lagging wavefront in a sound-deadened room using a discrimination paradigm. We estimated the minimum audible angle, or MAA (Mills, 1958), the smallest lateral difference in the position of a sound that listeners can detect reliably. Figure 1 illustrates the three conditions we used. In the single-burst condition, a sound was presented to one of two loudspeakers (R or L) to the right or left of a middle reference azimuth (M). The other two conditions extended the task to precedence-effect burst pairs: In *lead discrimination*, the leading signal was presented from either the left or the right, the lagging signal from the middle. In *lag discrimination*, the complementary task, the leading sound was presented from the middle, the lagging signal from the left or right. Lag discrimination thresholds have been found to be higher than those for single signals (Perrott *et al.*, 1989); lead discrimination has not, to our knowledge, been measured previously.

We manipulated two variables that we thought might affect the difficulty of the MAA task: Azimuth and the presence of a standard. With single bursts, performance is best when the central location (M in Fig. 1) is midline, and declines as the azimuth of M increases (Bronkhorst, 1993; Mills, 1958). To our knowledge, MAAs for precedence-effect stimuli have not been measured off midline. In the present study, we used both midline and off-midline positions for all stimulus types.

In most MAA studies, the right or left comparison stimulus is preceded by a standard stimulus presented at a middle location. In the only study to evaluate the effect of such a standard, Hartmann and Rakerd (1989) found that it provided no benefit to listeners discriminating single-click stimuli at 0° azimuth. We speculated that this finding might

<sup>a)</sup> Present address: Eaton-Peabody Laboratory, Mass. Eye & Ear Infirmary, 243 Charles St., Boston, MA 02114 and Dept. Biomedical Engineering, Boston University, 44 Cummings St., Boston, MA 02215.

<sup>b)</sup> Present address: Department of Psychology, Brooklyn College, Brooklyn, NY 11210.



Single burst: R or L  
 Lag discrimination:  
 <lead: M> <lag: R or L>  
 Lead discrimination:  
 <lead: R or L> <lag: M>

FIG. 1. The three no-standard MAA tasks in the present study. Listeners always had to discriminate bursts from the left (L) or right (R) speakers, which were presented either in isolation, or as the lead component of a burst pair, or as the lag component of a pair.

be specific to the azimuth and stimulus type studied by Hartmann and Rakerd. If the straight-ahead location serves as a perceptual anchor, discrimination performance might profit from a standard only for peripheral stimuli. Standards might also be more helpful with burst pairs than single bursts, because the former appear to many listeners to be more diffuse and difficult to localize (Freyman *et al.*, 1991; Perrott *et al.*, 1989).

## I. METHOD

### A. Subjects

Four subjects participated in the experiment. Three (two males, one female) were undergraduate students aged 19–21 who had worked as research assistants in similar experiments; the fourth was a middle-aged author (NAM). All subjects except NAM had pure-tone air-conduction detection thresholds less than or equal to 15 dB HL (*re*: ANSI, 1969) at 0.25, 0.5, 1.0, 2.0, 4.0, 6.0, and 8.0 kHz, and had no more than 10 dB difference between the two ears at any of the test frequencies; NAM's threshold at 8.0 kHz was 25 dB HL. Although all subjects were somewhat familiar with research on spatial hearing, only NAM was aware of the experimental hypotheses. The subjects and both authors served as experimenters.

### B. Apparatus

The study was conducted in a 3.5 m×4.0 m sound-deadened room; for a description, see Ashmead *et al.* (1987). Three matched loudspeakers (Radio Shack model Minimus-7) were suspended from an apparatus that covered 110° of a 1.65-m radius circle. Each loudspeaker was 10 cm (4°) wide and 18 cm (7°) high. One loudspeaker was always placed at the middle of the arc, the other two at equal distances to the left and right. For trials on which the left and right loudspeakers were less than 4° from the middle, they were suspended 4° below the middle loudspeaker.

The subjects were seated at the center of the circle defined by the arc containing the loudspeakers. They faced the apparatus, which was covered by a dark curtain to hide the loudspeakers. Loudspeaker locations were changed manually between trials.

## C. Stimuli and trial sequence

Stimuli were 6-ms wideband (500 to 8500 Hz) noise bursts with 2-ms rise-fall times. They were computer generated with 16-bit precision, converted to analog form at 20 kHz (TTES-QDA1), low-pass filtered at 8500 Hz (TTEJ1390), and tape-recorded (Teac X-300). During testing, the prerecorded stimuli were amplified and played back from the same tape recorder over the loudspeakers; most of their energy was below 3000 Hz. The sounds were presented at a level of 50–52 dBA over a background level of 28 dBA, measured at the approximate position of the subject's head.

The time sequence for a trial for each of the three stimulus conditions is shown in Figure 2. In lead- and lag-discrimination trials, the two bursts were selected independently for each trial from a long segment of the noise. There was a 4-ms delay between the first and second stimuli, resulting in a 2-ms overlap between them.

In no-standard conditions [Fig. 2(a)] a single stimulus of the appropriate type was presented on each trial, randomly from the left or right. Subjects responded "left" or "right" verbally, and visual feedback was provided after correct responses. In conditions with a standard [Fig. 2(b)], the test stimulus was preceded by a single burst from the middle loudspeaker.

## D. Design

We examined stimulus condition (single-burst, lead-discrimination, lag-discrimination), presence of a standard, and azimuth in a completely within-subject design. The location of the middle speaker was set to 0°, 25°, or 50° azimuth in the with-standard conditions, 0° and 50° in the no-standard conditions. At 0° azimuth, the observer faced the (invisible) center loudspeaker. At other azimuths, the observer's chair was rotated to the left by the desired amount, so that all stimuli arose from the right hemifield. For all positions, listeners were instructed to look straight ahead at a marker on the curtain, but their heads were not physically restrained.

For the five combinations of azimuth and standard, MAAs were obtained for single-burst, lead, and lag discrimination. These conditions were randomly permuted separately for each subject. Subjects NAM, DDM, and JPR were tested on three such permutations, subject HAM on two blocks. Testing time was 10 to 15 h per listener, including 2 h of practice.

## E. Adaptive method

We used an eclectic psychophysical method to estimate thresholds: The decision to change level (*i.e.*, move the left and right loudspeakers) was based on a staircase, the new level was chosen with modified PEST rules, and our threshold estimates used a maximum-likelihood method.

The staircase procedure was the classic 2-down, 1-up method of Levitt (1971), which seeks the 71% point on a psychometric function. The initial angle, selected to yield high (if possible, perfect) accuracy, was 10° for single-burst/0° and lead-discrimination/0° conditions, 30° for other single-burst and lead-discrimination conditions, and 55° for

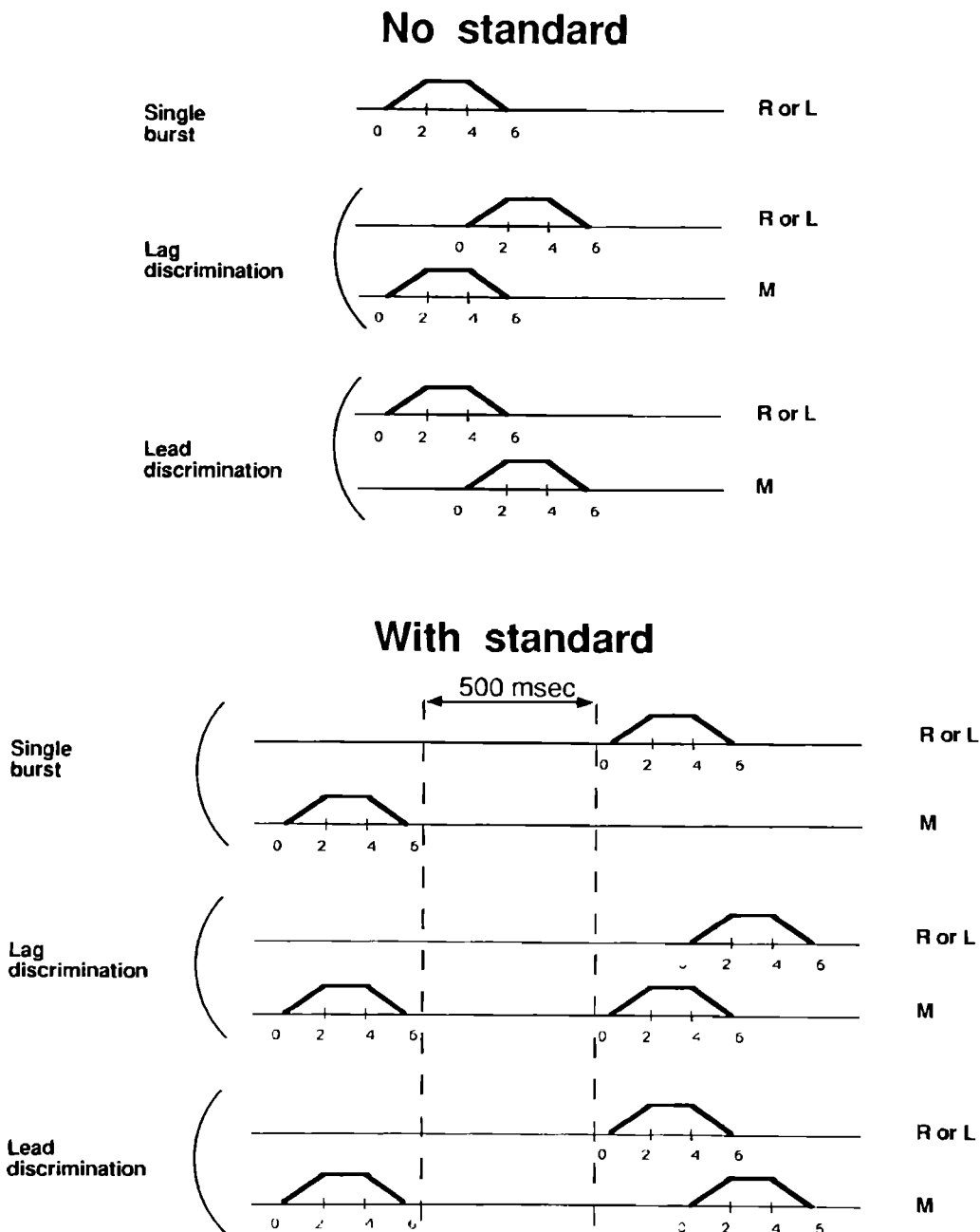


FIG. 2. Sequence of events on a single trial for each experimental condition. Lines marked M indicate events that arose from the middle speaker on every trial; lines marked R or L indicate events that arose from the right or left speaker, the listener's task being to determine which. Numbers along the lines are ms.

lag discrimination. The PEST rules (Taylor and Creelman, 1967; Macmillan and Creelman, 1991, Chap. 8) for choosing the new angle were as follows: (1) The minimum angle was  $0.5^\circ$  and the maximum angle was  $55^\circ$ . If PEST requested a level outside this range, the minimum or maximum was presented instead. (2) Standard PEST rules were used to change (double or halve) the step size, except that an incorrect response at  $0.5^\circ$  resulted in a change to  $2^\circ$ , not  $1^\circ$ . The minimum change in angle was  $0.5^\circ$ . (3) The experimental run was terminated after seven reversals (a reversal is an increase in angle following a decrease, or vice versa).

Maximum-likelihood estimates of thresholds used all the data from an experimental run, with the assumption that the psychometric function was logistic in form; specifically, if  $p$

is proportion correct, then  $p/(1-p)$  vs angle was a linear function on log coordinates. An examination of psychometric functions revealed that a slope of 0.7 on these coordinates provided a good fit at all angles. For each experimental run we found the psychometric function of this form for which the data were most likely, and estimated threshold as the 71% point on that function.

Maximum-likelihood is often the best approach for threshold estimation, and has long been used in combination with PEST (Hall, 1981). In our particular application, the method had a special advantage. For conditions in which the threshold was either very low or very high, we were sometimes unable to obtain complete psychometric functions. The apparatus did not allow us to present angles larger than  $55^\circ$ ,

TABLE I. Average MAAs, in degrees, for each subject and stimulus condition.

Subject	Standard?	Azimuth			
		(deg)	Single	Lead	Lag
DDM	yes	0	2.06	1.51	4.86
	yes	25	1.50	1.29	9.12
	yes	50	2.07	2.34	18.23
	no	0	1.38	2.37	16.07
	no	50	2.44	1.92	46.59
HAM	yes	0	1.43	3.06	6.98
	yes	25	3.44	3.56	9.94
	yes	50	1.92	6.02	41.09
	no	0	7.12	1.61	11.92
	no	50	3.13	2.48	45.65
JPR	yes	0	1.42	0.93	9.62
	yes	25	1.19	4.53	6.00
	yes	50	1.90	1.80	38.64
	no	0	0.74	1.45	19.93
	no	50	3.53	2.19	25.26
NAM	yes	0	1.00	1.21	2.59
	yes	25	1.21	3.64	16.64
	yes	50	4.24	3.23	47.68
	no	0	1.14	1.55	20.77
	no	50	1.71	2.86	39.63
Mean	yes	0	1.48	1.68	6.01
	yes	25	1.84	3.13	10.42
	yes	50	2.53	3.35	36.41
	no	0	2.60	1.74	17.17
	no	50	2.70	2.36	39.28

and we did not attempt to present angles smaller than 0.5°. Thus an upward reversal sometimes occurred too soon at small angles, and a downward reversal too soon at large angles. Averaging reversals, a common data-reduction method for staircase procedures, would therefore have overestimated low thresholds and underestimated high ones. Maximum-likelihood estimation takes as its input the numbers of correct and incorrect responses at each angle, and is, to a first approximation, unaffected by the particular stimuli presented.

## II. RESULTS

Estimates of the MAA for all subjects and conditions are given in Table I, and the means across subjects are plotted in Fig. 3. The reliability of differences among the various conditions was evaluated with two separate ANOVAs on individual means. The major analysis was 3-way [standard (presence, absence) × azimuth (0°, 50°) × stimulus type (single-burst, lead-discrimination, lag-discrimination)]; a secondary 2-way analysis [azimuth (0°, 25°, 50°) × stimulus type] included the standard-present conditions only.

**Stimulus type:** As is obvious in Fig. 3, thresholds in lag discrimination were higher than those in single-burst and lead discrimination, which did not differ from each other. In the ANOVA, stimulus type showed an overall significant effect [ $F(2,6)=29.2, p<0.001$ ]. MAAs were significantly higher in lag discrimination than in either single-burst [ $t(1,3)$

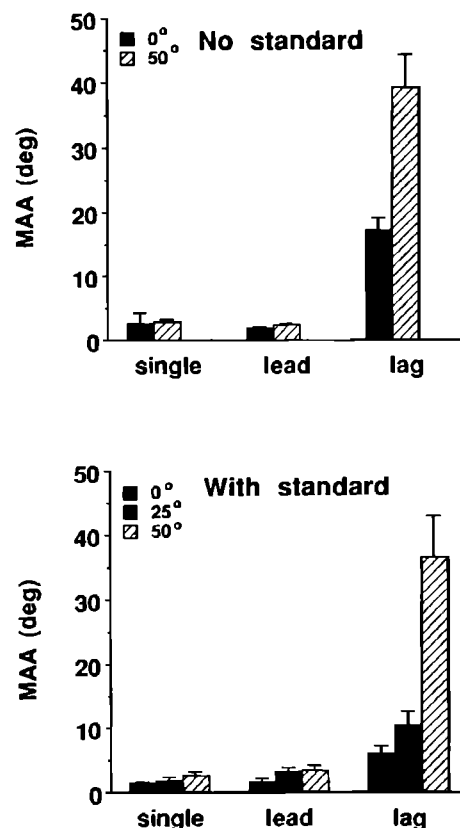


FIG. 3. Average MAAs for all single-burst, lead-discrimination, and lag-discrimination tasks, with and without a standard. Error bars indicate one standard error.

$=27.2, p<0.001$ ] or lead discrimination [ $t(1,3)=32.7, p<0.001$ ], but lead discrimination was not significantly different from single-burst.

**Standard:** The effect of the standard varied substantially (but for the most part unreliably) across conditions. The benefit of the standard was measured by the geometric mean ratio of with-standard and no-standard MAAs. This benefit was 27% overall, 76% in lag discrimination, and 73% at 0°. The only reliable improvement, however, was a 186% effect for lag discrimination at 0° [ $F(3)=4.1, p<0.02$ ].

**Azimuth:** Thresholds were higher at 50° than at 25° or 0°, especially so for lag discrimination. In the 3-way ANOVA, azimuth showed a significant effect overall [ $F(1,3)=46.8, p<0.006$ ], and for lag discrimination separately [ $F(1,3)=41.6, p<0.008$ ]. The two-way ANOVA confirmed these conclusions, and showed that MAAs at 25° and 0° did not differ.

## III. DISCUSSION

Our discussion of the data has two parts. First, we consider the qualitative effects of standard, stimulus type, and azimuth, relating our results to the data and theoretical constructs of others. Second, we adapt a model by Shinn-Cunningham *et al.* (1993) to interpret the differences between the single-burst, lead-discrimination, and lag-discrimination conditions in terms of their perceptual effects.

## A. Relation to previous literature

### 1. Effects of standard stimuli

The benefit of the standard varied greatly in this study, reaching significance only in one condition (lag discrimination at  $0^\circ$ ). As Hartmann and Rakerd (1989) have pointed out, detection theory predicts that the presence of a standard will lead to either worse performance (if observers subtract the effects of the standard and comparison stimuli) or no change (if they ignore the standard). Our failure to detect a reliable effect might simply mean that observers made no use of the standard, a conclusion of some interest in view of the preponderance of studies that do include standards.

One finding in the literature may be analogous to the (statistically insignificant) 76% benefit of the standard in lag discrimination. Freyman *et al.* (1991) and Wolf (1988) reported lower echo thresholds (that is, lag-discrimination thresholds) for click pairs preceded by a train of single clicks than for those preceded by a train of click pairs. Freyman *et al.* (1991) proposed that the advantage of the single-click train resulted from a contrast effect that enhanced perception of the lagging sound. In the lag condition of the present study, a single-burst standard was followed by a burst-pair target. Thus a contrast effect could account for the benefit of the standard we observed in lag discrimination, although it does not explain why the benefit at  $0^\circ$  is so much larger than at  $50^\circ$ .

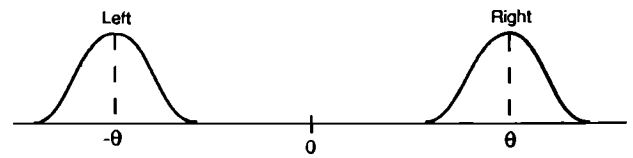
When standards have been found to improve performance on other tasks, they have often been said to aid "memory." An examination of experiments in which perceptual anchors have been diagnosed suggests that we may not have employed the most powerful test of this notion. For example, perceptual anchors in auditory intensity (Braidia *et al.*, 1984), and for speech continua (Macmillan *et al.*, 1988) have an effect only when the range of stimuli is large, and in our situation the range was somewhat restricted. Natural experiments in which to investigate the anchor possibility further are localization and discrimination over a wider range of azimuths.

### 2. Effects of stimulus type and azimuth

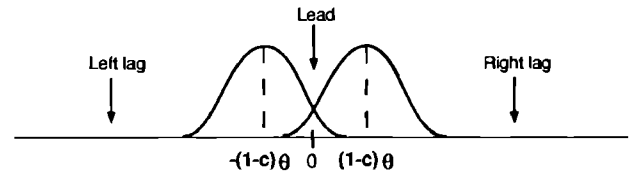
Our single-burst thresholds of  $1.5^\circ$  to  $2.7^\circ$  are consistent with those reported by other investigators (Gardner, 1968; Mills, 1958), although values less than  $1^\circ$  have also been reported (Litovsky, 1994; Perrott *et al.*, 1989; Hartmann and Rakerd, 1989). Elevated thresholds at  $50^\circ$  have been previously reported for clicks (Hafta *et al.*, 1988, 1991) tone pips (Mills, 1958), and pure tones (Chandler *et al.*, 1993). Overall, data from this and other experiments suggest that thresholds are lower for clicks than for pure tones. This difference may result from the more abrupt onsets of noise and click stimuli: Our bursts had rise-fall times of 2 ms, whereas Mills' stimuli required 70 ms and those of Chandler *et al.* (1993) 10 ms to reach maximum. As several investigators have pointed out, localization precision is facilitated by quick onsets (Hafta and Dye, 1983; Hafta and Buell, 1990; Rakerd and Hartmann, 1986).

The good performance in lead discrimination and the difficulty of lag discrimination are both evidence for a strong

### Single-burst discrimination



### Lag discrimination



### Lead discrimination

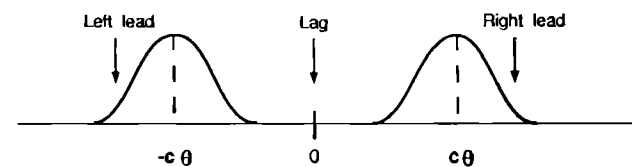


FIG. 4. The Shinn-Cunningham *et al.* (1993) model for the perceptual representation of precedence-effect burst pairs. The lateral position of the auditory image is a weighted average of the lead and lag positions, the weight of the lead (denoted  $c$ ) being greater.

precedence effect: The presence of an echo that carries no valuable localization information does not impair performance, and it is more difficult to make a decision on the basis of the echo than on the basis of the leading wavefront. Perrott *et al.* (1989) also found that lag-discrimination MAAs were higher than those for single bursts, but their thresholds were lower than ours, typically only  $2^\circ$  to  $4^\circ$ . To our knowledge, no one has previously reported lead-discrimination data.

Finally, azimuth made little difference in single-burst or lead discrimination, whereas it affected lag discrimination heavily. Listeners reported anecdotally that in lag discrimination the fused sound was perceptually "pulled" toward the location of the lagging burst. It is possible that at increased distance from midline the pulling effect is diminished and thresholds therefore increase.

## B. Interpretation using a model for the perceptual representation of precedence-effect stimuli

Since the original Wallach *et al.* study in 1949 it has been known that echoes shift the perceived location of a fused pair of stimuli. This observation is the foundation of an elegant recent model for lateralization under precedence conditions by Shinn-Cunningham *et al.* (1993). A slightly modified version of this model is illustrated in Fig. 4. In the top panel the lateral position of a single burst is described by a distribution whose mean is  $\pm\theta$  degrees from a middle reference point.

TABLE II. Estimates of  $c$  by three methods.<sup>a</sup>

Azimuth (degrees)	$N$	Single/lag [Eq. (2a)]	Single/lead [Eq. (2b)]	Lag/lead [Eq. (2c)]	Average
0	7 <sup>b</sup>	0.81(0.06)	0.86(0.16)	0.83(0.04)	0.83
25	4	0.80(0.06)	0.68(0.23)	0.75(0.07)	0.74
50	8	0.92(0.01)	1.04(0.15)	0.93(0.01)	0.96
Average <sup>c</sup>		0.85	0.90	0.86	0.87

<sup>a</sup>Figures in parentheses are approximate standard errors, calculated by treating all estimates (even those from the same subject) as independent.

<sup>b</sup>Data from observer HAM, 0°, no standard, are not included.

<sup>c</sup>Weighted by  $N$ .

Under conditions of the precedence effect, the leading and lagging bursts are perceived as one fused sound whose location is a weighted average of the positions of the two components; the weight given to the leading burst is denoted  $c$ , the weight of the lagging one  $1-c$ . The middle panel of Fig. 4 shows the representation for lag discrimination: The echo pulls the distribution away from the middle to  $\pm(1-c)\theta$ . If the precedence effect were complete (that is, if the lag had no effect at all),  $c$  would equal unity,  $1-c$  would equal zero and this task would be impossible. In lead discrimination (bottom panel), the echo moves the distributions from  $\pm\theta$  to  $\pm c\theta$ . Under complete precedence,  $c$  would equal 1 and this bottom panel would look exactly like the top one.

According to the model, two factors influence discrimination: The inherent variance of the distributions; and the pulling effect of the lag, measured by  $1-c$ . We first use the model to assess these two parameters from our data, asking whether the estimates we obtain are reasonable. For the single bursts, only the inherent variance is relevant, and single-burst thresholds can be used to estimate the variability in the perceptual representations. Our listeners' thresholds in the various single-burst conditions averaged 2.23 deg, so the two sounds being discriminated differed in azimuth by twice that, or 4.5°. The adaptive procedure estimated the point on the psychometric function at which  $d' = 1.1$ ; the standard deviation of the underlying distributions is therefore approximately 4.5°/1.1, or 4°. In their headphone pointer-adjustment study, Shinn-Cunningham *et al.* (1993, p. 2926) estimated the standard deviations of their subjects to be between 20 and 60  $\mu$ s. According to Mills (1972, Fig. 2), one degree azimuth corresponds to about 7.3  $\mu$ s, so the standard deviations estimated by Shinn-Cunningham *et al.* are between 3° and 8°. Our measure of variability appears reasonable.

The parameter  $c$ , the relative weighting of the lead wavefront, can be estimated by comparing any two of the three stimulus conditions, so three correlated estimates of  $c$  are available. The calculation is as follows:  $d'$  is the distance between the means of the distributions shown in Fig. 4 (divided by their standard deviations, which we set equal to unity):

$$d'_{\text{single}} = 2\theta, \quad (1a)$$

$$d'_{\text{lag}} = 2(1-c)\theta, \quad (1b)$$

$$d'_{\text{lead}} = 2c\theta. \quad (1c)$$

We make the common assumption that our threshold estimates are inversely related to  $d'$ , as would be true if the psychometric functions, plotted as  $d'$  vs angle, were straight lines through the origin. Then the thresholds in the three conditions are related by

$$\text{thr}(\text{single})/\text{thr}(\text{lag}) = 1 - c, \quad (2a)$$

$$\text{thr}(\text{single})/\text{thr}(\text{lead}) = c, \quad (2b)$$

$$\text{thr}(\text{lead})/\text{thr}(\text{lag}) = (1 - c)/c. \quad (2c)$$

Estimates of  $c$  from Eqs. (2) are listed in Table II. [Data from one subject (HAM) in one condition (0°, no standard) were omitted because her single-burst performance was inexplicably high, compared to other subjects and to her performance on other conditions.] The three equations give very similar estimates of  $c$ , with an average of 0.87.

Shinn-Cunningham *et al.* (1993) calculated  $c$  from data reported by other investigators, collected using both adjustment and discrimination paradigms. In the original adjustment experiment, Wallach *et al.* (1949) presented 1-ms clicks with 2-ms lead-lag delays and a fixed lag interaural delay, or ITD (the lateralization variable corresponding to azimuth). Lead ITD was varied to find a combination of the two ITDs that resulted in a centering of the auditory image. Estimates of  $c$  ranged from 0.85 to 0.95. Shinn-Cunningham *et al.* obtained similar values from the results reported by Yost and Soderquist (1984) and Zurek (1980), and from their own data. In discrimination experiments (Gaskell, 1983; Saberi and Perrott, 1990; Shinn-Cunningham *et al.*, 1993; Zurek, 1980),  $c$  ranged from 0.7 to 1.0 at ITDs of 0 to 10 ms.

In Shinn-Cunningham *et al.*'s reanalysis of the literature, there was a tendency for  $c$  to increase with the absolute difference between the ITD of the lead and the ITD of the lag. Thus large MAAs would be expected to produce large values of  $c$ . In our experiment, large MAAs occurred in the off-midline conditions, especially 50° azimuth, and these conditions should therefore produce high values of  $c$ . Table II shows that  $c$  is indeed greater at 50° azimuth than elsewhere, and that this is true no matter which pair of conditions is used to estimate  $c$ .<sup>1</sup>

One important aspect of our listeners' intuitions is not captured by the model. As many writers (e.g., Blauert, 1983; Lindemann, 1986; Yost and Soderquist, 1984) have noted, precedence-effect sounds are perceptually larger or more diffuse than single-burst sounds. We considered the possibility

that this diffuseness might be captured, in the model, by increased variance of the distributions in precedence conditions. If the perceptual variance in the lead- and lag-discrimination conditions were greater than in the single-burst case, then the estimates of  $c$  obtained from Eq. (2a) and (2b) would be systematically smaller than those obtained from Eq. (2c). It is evident from Table II that no such difference was observed. One interpretation of this nonfinding is that the model variance represents *trial-to-trial* variability in location, not spatial extent within a trial.

#### IV. CONCLUSION

In conclusion, the model (with equal variances) serves to unify the results from our various stimulus conditions. Performance in lead discrimination is almost, but not quite, as good as that with single bursts. The discrepancy, which must be due to the presence of the lag, can in fact be used to predict lag discrimination, using the assumption that the lag has a pulling effect. The amount of pulling does not depend on the experimental task (which would invalidate the model), but does depend on azimuth, and doubtless on many other stimulus factors.

#### ACKNOWLEDGMENTS

We are grateful to Rachel Clifton for the use of her laboratory, and to Rachel Clifton, Steve Colburn, Richard Freyman, Wesley Grantham, Barbara Shinn-Cunningham, and Pat Zurek for helpful comments on an earlier version of this manuscript. Many thanks to Daniel McCall, Heather McNatt, and Joseph Ryan for their assistance in data collection, and to Kuan Chung-Huei for technical support. This work was supported in part by NSF (grants BNS-8812543 to Rachel Clifton and Richard Freyman and DBS-9212043 to Neil Macmillan), by NIH (National Research Service Awards to each author), and by the PSC-CUNY Research Award Program (to Neil Macmillan). A paper based on these data was presented at the 125th meeting of the Acoustical Society of America in Ottawa, Canada (Litovsky and Macmillan, 1993).

<sup>1</sup>Note that lag thresholds are greater than lead thresholds, so that sounds arise from larger azimuths in the lag condition. If  $c$  does depend on azimuth, then Eq. (2c) which combines lag and lead data, is suspect as a method for examining the effect of azimuth on  $c$ . In spite of this problem, both the overall estimate of  $c$  and its dependence on azimuth are about the same for Eq. (2c) as for (2a) and (2b).

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