Comparing monaural and interaural temporal windows: Effects of a temporal fringe on sensitivity to intensity differences

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In an effort to provide a unifying framework for understanding monaural and binaural processing of intensity differences, an experiment was performed to assess whether temporal weighting functions estimated in two-interval monaural intensity-discrimination tasks could account for data in single-interval interaural intensity-discrimination tasks. In both tasks, stimuli consisted of a 50-ms burst of noise with a 5-ms probe segment at temporal positions ranging between the onset and offset of the overall stimulus. During the probe segment, one monaural interval or binaural channel of each trial contained an intensity increment and the other contained a decrement. Listeners were instructed to choose the interval/channel containing the increment. The pattern of monaural thresholds was roughly symmetrical (an inverted U) across temporal position of the probe but interaural thresholds were substantially higher for a brief time interval following stimulus onset. A two-sided exponential temporal window fit to the monaural data accounted for the interaural data well when combined with a post-onset-weighting function that described greatest weighting of binaural information at stimulus onset. A second experiment showed that the specific procedure used in measuring fringed interaural-intensity-difference-discrimination thresholds affects thresholds as a function of fringe duration and influences the form of the best-fitting post-onset-weighting function. © *2005 Acoustical Society of America.* [DOI: 10.1121/1.2047247]

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I. INTRODUCTION

The temporal resolution of the auditory system is limited in that the system smoothes rapid fluctuations in intensity. One manifestation of this smoothing is that the just-detectable change in intensity of a tonal or noise pedestal increases as the duration of the change decreases. This limitation in temporal resolution can be modeled as a temporal window that integrates intensity information over a brief time interval. A number of attempts have been made to characterize the duration and shape of the temporal window on the basis of data for monaural detection of a click in noise (e.g., Penner *et al.*, 1972; Penner and Cudahy, 1973), monaural tone-in-noise detection data (e.g., Moore *et al.*, 1988; Plack and Moore, 1990) and monaural intensity-discrimination data (e.g., Oxenham, 1997). The temporal window often is modeled as asymmetrical in order to account for differences in the influence of information that precedes and follows the signal or intensity change to be detected. While models incorporating temporal windows have been used to account for the results of various detection and discrimination tasks such as those just cited, the parameters of the best-fitting temporal window depend on the specific task.

Temporal resolution for changes in the interaural intensity difference carried by a stimulus also is limited (Grantham, 1984; Zurek, 1980; Bernstein *et al.*, 2001). In conditions similar to the monaural increment- and decrement-detection studies just described, Zurek (1980) and Akeroyd and Bernstein (2001) measured the sensitivity of listeners to changes in the binaural information of a 5-ms burst of broadband noise that was embedded in an otherwise-diotic 50-ms noise burst (their "Both-fringe" conditions). In both sets of results, sensitivity to changes in either the interaural time difference (ITD) or interaural intensity difference (IID) of the probe segment was greatly diminished when the onset of the probe segment occurred just after and within about 10 ms of the overall stimulus onset. In separate conditions, Akeroyd and Bernstein (2001) presented a 5-ms probe that was either preceded or followed by a diotic noise of varying duration (a forward or backward fringe; their "Forward-only" and "Backward-only" conditions) such that the probe occurred at the offset or onset of the overall stimulus. In both cases, they found that sensitivity to changes in the binaural information of the probe decreased with increasing duration of the diotic forward or backward fringe. Akeroyd and Bernstein were able to fit their data and those of Zurek with a model that consisted of a combination of a temporal window and a post-onset-weighting function that described a decrease in the weighting of information following the onset of the stimulus, although different best-fitting parameter values were estimated in order to account for the two sets of data. Furthermore, while Zurek posited that sensitivity to changes in the interaural configuration of the probe segment was determined only by the diotic noise that preceded the probe, the data of Akeroyd and Bernstein as well as their model results showed that processing of the binaural information carried by the probe was influenced by diotic portions of the stimulus that both preceded and followed the probe.

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The present study, motivated by the study of Akeroyd and Bernstein (2001), seeks to determine whether a relationship exists between sensitivity to changes in the IID of a brief segment of a stimulus like that described earlier and sensitivity to changes in the monaural intensity of a stimulus with similar temporal characteristics, or more specifically, whether a common set of weighting functions can account for data gathered in the two listening conditions. The comparison is made using data gathered in a two-interval monaural intensity-discrimination task and a single-interval IID-discrimination task. Stellmack *et al.* (2004) observed that monaural and interaural comparisons of intensity both exhibit Weber's law for broadband noise and the near-miss to Weber's law for pure tones when monaural and binaural performance is measured using procedures that facilitate direct comparison of the data. The underlying assumption was that monaural intensity-discrimination thresholds measured in a two-interval forced-choice procedure and IID-discrimination thresholds measured in a single-interval task involve the presentation of equal amounts of information on each trial. Both procedures present two samples of intensity to the listener on each trial, samples that are separated in time in the monaural task and separated across ears in the binaural task. As a result, the presumed decision statistics in the two tasks are identical. [Unlike the Akeroyd and Bernstein (2001) study, ITD-discrimination thresholds were not measured in the present study.] It will be seen that a temporal window alone accounts well for the monaural intensity-discrimination thresholds while a temporal window with the same parameters combined with a weighting function that described greatest weighting of binaural information at stimulus onset yielded good predictions of the binaural intensity-discrimination thresholds. This yields a simple framework for understanding the relationship between the auditory processing that underlies the monaural and binaural intensity-discrimination tasks. A second experiment described in the following assesses the effects of procedural differences between the present study and those of Zurek (1980) and Akeroyd and Bernstein (2001) in order to attempt to account for differences between the weighting functions derived for the various sets of data.

II. EXPERIMENT 1: MONAURAL AND INTERAURAL TEMPORAL WINDOWS

A. Methods

The temporal and spectral characteristics of the binaural stimuli were similar to those in the "Both-fringe" conditions of Akeroyd and Bernstein (2001) and the stimulus envelopes are depicted in the upper portion of Fig. 1. In the single-interval binaural procedure used here, the signal was a 50 -ms burst of broadband noise that was diotic except for a 5 -ms probe segment that carried a nonzero IID. Listeners were instructed to indicate whether the IID of the probe on each trial favored the left or right ear. (In contrast, Akeroyd and Bernstein used a multi-interval procedure in which listeners discriminated diotic stimuli from dichotic stimuli.) The IID in the probe segment was produced by decrementing the intensity of the signal in one ear and incrementing the intensity at the other ear during the probe segment (relative to the fringe), with the ear receiving the incremented probe chosen randomly from trial-to-trial.

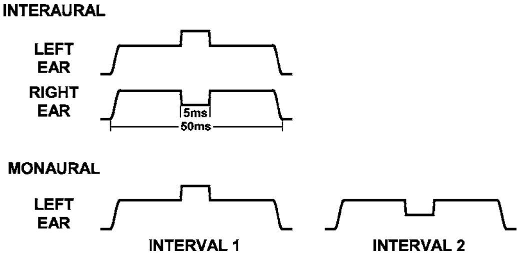

FIG. 1. A schematic illustration of the envelopes of the stimuli (noise bursts) presented in the IID-discrimination task (upper portion) and monaural intensity-discrimination conditions (lower portion). Stimuli are not drawn to scale. See the text for a complete description.

The envelopes of the stimuli presented in the two-interval monaural intensity-discrimination procedure are depicted in the lower portion of Fig. 1. The monaural condition can be considered as a situation in which the left- and right-ear stimuli of the binaural condition were presented to only the left ear in two separate temporal intervals of each trial. The interval that contained the incremented probe was varied randomly from trial-to-trial and the listeners' task was to identify which interval contained the intensity increment.

For each stimulus presentation, a 50-ms broadband noise signal was generated in the frequency domain by drawing amplitudes from a Rayleigh distribution and starting phases from a uniform distribution for all components below 8 kHz. A time-domain signal was produced by applying an inverse fast Fourier transform (FFT) to the resulting spectrum. Cosine-squared ramps, 1 ms in duration, were applied to the onset and offset of each noise signal. Thresholds were measured for forward-fringe durations of 0, 0.5, 1, 2.5, 5, 7.5, 10, 15, 20, 25, 30, 35, 40, and 45 ms. (In this paper, the term "forward fringe" refers to temporal portions of the stimulus that precede the probe while "backward fringe" refers to portions that follow the probe.) In each case, the duration in milliseconds (ms) of the backward fringe was computed as follows: overall duration of stimulus (50 ms) minus probe duration (5 ms) minus forward-fringe duration. (The exact durations described could not be achieved because of the 44.1-kHz sample rate. As a result, the durations of the forward fringe, probe, backward fringe, and ramps in ms were rounded up to the duration corresponding to the nearest integer number of samples.) No ramps were applied to the onset or offset of the 5-ms probe segment (unless those coincided with ramps at the onset or offset of the entire 50 -ms signal).

The difference in intensity between the incremented and decremented probe segments was varied adaptively from trial-to-trial using a three-down-one-up procedure designed to track to the 79.4% correct point on the psychometric function (Levitt, 1971). The intensity difference between the incremented and decremented probe segments was expressed in decibels (dB) relative to the intensity of the decrement [$10 \log(\Delta I/I)$]. These units were chosen because they commonly are used to express monaural intensity-discrimination thresholds. Furthermore, because there is no absolute zero in

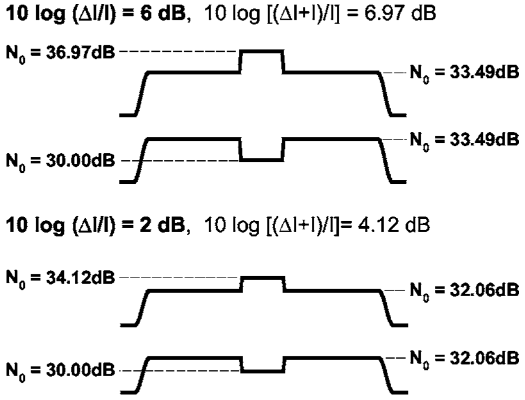

FIG. 2. A schematic illustration of how levels were determined for two different signal levels, $10\log(\Delta I/I)=6$ dB (upper portion) and 2 dB (lower portion). The absolute level of the decrement was held constant and the levels of the fringe and increment were adjusted based on the signal level determined by the adaptive procedure.

these units as there is for the dB difference between intensities $\{10\log[(\Delta I+I)/I]\}$, units in which IID is usually expressed, there is no concern that the adaptive procedure will track to zero. In each block of trials, the intensity difference initially was varied in steps of 4 dB and reduced to 2 dB after four reversals until a total of 12 reversals occurred. The intensity difference at the start of each block of trials was set to a well-detectable level (6–8 dB above the expected threshold) and adjusted as necessary in subsequent blocks based on the ongoing performance of each listener. The mean of the intensity differences in units of $10\log(\Delta I/I)$ at the final eight reversals was computed as the estimate of threshold. Four such estimates were obtained in each experimental condition and the mean of those four estimates was taken as the final threshold estimate.

Although the lower-intensity probe segment is described here as a "decrement" or "decremented," that lower intensity was fixed across trials. Thus, the decrement was relative to the fringe, not in absolute terms. This was done so that threshold intensity differences (between the higher- and lower-intensity probe segments) could be specified, if desired, relative to a fixed reference intensity (that of the lower-intensity probe), as in Stellmack *et al.* (2004). Therefore, in the course of the adaptive procedure, the intensity of the decremented portion of the probe was held constant (30 dB spectrum level) and the intensities of the fringe and incremented portion of the probe were adjusted appropriately (see Fig. 2). After the spectrum level of the incremented probe was determined (based on the magnitude of the current increment in the adaptive procedure), the spectrum level of the fringe was set to the mean of the spectrum levels of the incremented and decremented probes. Thus the difference between the fringe and decrement was equal to the difference between the increment and fringe in terms of both the dB difference $\{10\log[(\Delta I+I)/I]\}$ and Weber fraction $[10\log(\Delta I/I)]$. Akeroyd and Bernstein (2001) held the spectrum level of the fringe constant and varied the spectrum levels of the incremented and decremented probes while in the present experiment the spectrum level during the decrement was held constant. Given that Stellmack *et al.* (2004) found no level effects for binaural intensity-discrimination thresholds with noise, it is believed that this procedural difference is not important.

Stimuli were generated digitally within MATLAB at a sample rate of 44.1 kHz and converted to analog signals on a PC equipped with a high-quality, 24-bit sound card (Echo Audio Gina). Stimuli were presented over Sony MDR-V6 stereo headphones to listeners seated in an IAC sound-attenuating chamber. Each block of trials was initiated by the listener. On each trial, a "ready" light flashed on the computer screen for 250 ms followed by a 100-ms pause after which a trial was presented. Listeners entered their responses on the computer keyboard at which time the correct response was indicated on the screen. Listeners were run in 2-h sessions, during which approximately 12–14 blocks of trials were run, until all stimulus conditions were completed.

In case performance in the single-interval binaural task could be facilitated by allowing each listener to establish an estimate of the perceptual midline, before each block of binaural trials each listener was allowed to listen to a diotic broadband noise burst (500 ms, 20 dB spectrum level) and he or she was instructed to adjust the headphones so that the stimulus produced an intracranial image at the center of his or her head. Listeners were allowed to listen to the diotic stimulus until they were satisfied that the headphones were positioned properly at which time a block of binaural trials was initiated.

The four listeners consisted of the first and third authors (S2 and S1, respectively) and two undergraduate students (one female and one male) from the University of Minnesota who were paid to participate in the study. All listeners had pure-tone thresholds of 15 dB HL or better at octave frequencies from 250 to 8000 Hz. Listeners were allowed to practice in a variety of the monaural and binaural conditions until their thresholds stabilized. Very little practice was required for this set of listeners to reach asymptotic performance. Listener S1 ran two blocks of all the monaural conditions in a pseudorandom order followed by two blocks of all the binaural conditions in a pseudorandom order, and then he ran two additional blocks of the monaural and binaural conditions. Listeners S2, S3, and S4 ran two blocks of all the monaural conditions in a pseudorandom order followed by two additional blocks of the same monaural conditions, then they ran all of the binaural conditions in the same way.

B. Results

The individual data are shown in Fig. 3 and the mean data are shown in Fig. 4. Thresholds are plotted in units of $10\log[(\Delta I+I)/I]$, the difference between the spectrum levels of the decrement and increment. The right-hand ordinates of Figs. 3 and 4 scale these values as the Weber fraction $10\log(\Delta I/I)$, the units in which thresholds were measured adaptively, where ΔI is the just-detectable increment in intensity and I is the intensity of the decremented probe. In both figures, the monaural and interaural thresholds for the 5-ms probe segment in isolation are plotted as separate sym-

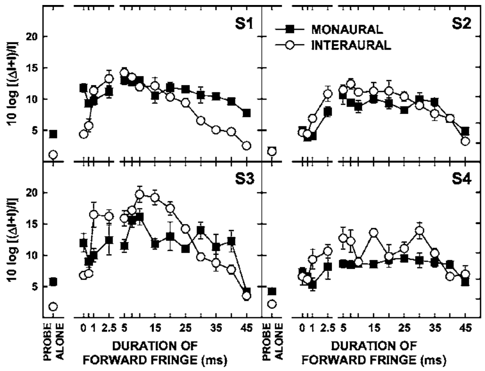

FIG. 3. Monaural (filled symbols) and interaural thresholds (open symbols) for four individual listeners as a function of forward-fringe duration. The ordinate is scaled in units of $10\log[(\Delta I+I)/I]$ on the left-hand side and $10\log(\Delta I/I)$ on the right-hand side. Thresholds for the probe alone are represented by the individual symbols on the left-hand side of each panel. Error bars represent standard errors of the mean for the four threshold estimates in each condition. Note the change in scale along the abscissa to expand the plots of the functions for short forward-fringe durations.

bols on the left-hand side of each panel. Note the breaks in the abscissas such that the scale is expanded between 0 and 2.5 ms.

The mean thresholds reflect the general trends of the individual data reasonably well, so the remaining comments will deal exclusively with the mean data of Fig. 4, although it should be noted that the individual data carry some exceptions to the trends of the mean data. All of the mean thresholds for the fringe conditions are higher than those for the corresponding "probe alone" conditions. The patterns of thresholds as a function of forward-fringe duration are similar for the monaural data (an inverted U) and interaural data (an asymmetrical inverted U) and are consistent with the data of Akeroyd and Bernstein (2001). The interaural thresholds are higher than the monaural thresholds for forward-fringe durations from 1 to 25 ms, while the monaural thresholds are higher than the interaural thresholds for the remaining (shorter and longer) forward-fringe durations. The monaural threshold for a 0-ms forward fringe was slightly elevated relative to monaural thresholds with forward fringes of 0.5 or 1 ms. The IID data of Akeroyd and Bernstein showed a similar upturn for a 0-ms forward fringe while the present interaural data did not. (It is difficult to compare the threshold values across studies because of procedural differences, a point that will be addressed in Experiment 2.)

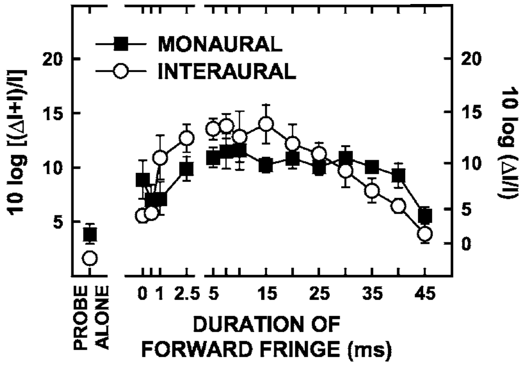

FIG. 4. Mean thresholds for four listeners in the same format as Fig. 3. Error bars represent standard errors of the mean.

C. Quantitative analysis: Methods

A quantitative analysis of the data was undertaken in the manner described by Akeroyd and Bernstein (2001). They showed that their interaural data were fit well by an asymmetric temporal window in combination with a post-onset-weighting mechanism that represented decreased weighting of binaural information for a brief period of time after the onset of the stimulus. Akeroyd and Bernstein performed a least-squares nonlinear regression on their data to estimate the parameters of the functions that would best fit their data. All fits in the present paper were performed on the mean data shown in Fig. 4. All equations and fitting procedures described in the following are identical to those described by Akeroyd and Bernstein unless otherwise noted. [See Akeroyd and Bernstein (2001) for additional details.]

Akeroyd and Bernstein (2001) gathered data only in binaural conditions so their fitting procedure operated on functions describing the instantaneous IID of their stimuli. In the present paper, functions were fit to the IID functions for the binaural stimuli and to functions describing the instantaneous intensity difference between corresponding temporal positions of the monaural stimuli. That is, for the monaural stimuli, the function describing the instantaneous intensity of the waveform containing the decrement was subtracted from that for the waveform containing the increment (as for the left- and right-ear stimuli of the binaural conditions) and the fitting procedure operated on this difference function. The instantaneous intensity differences were expressed in terms of $10\log[(\Delta I+I)/I)]$, the dB difference, for both the monaural and binaural conditions. In the following, the term "intensity difference" refers generally to a value of the difference function for the monaural or binaural conditions. The nature of these intensity-difference functions are discussed further at the end of this section.

The asymmetric temporal window was defined as follows:

$$w(\tau)=\begin{cases} e^{\tau/T_1}, & \tau<0 \\ e^{-\tau/T_2}, & \tau\geqslant 0 \end{cases}, \tag{1}$$

where τ is the time relative to the peak of the temporal window and T_1 and T_2 are the time constants determining the slopes of the temporal window before and after, respectively, the peak of the temporal window. It was assumed that the temporal window integrates the values of intensity difference carried by the probe segment with those of the surrounding noise, with the temporal window defining the relative weight given to the intensity difference at each temporal location within the window. The output of the temporal window, W, is

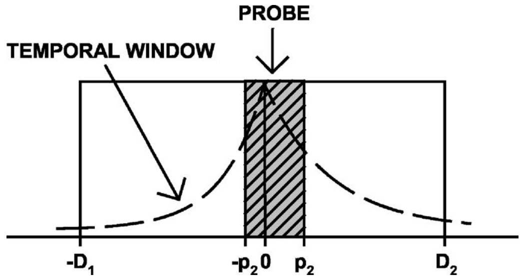

FIG. 5. A schematic illustration of the temporal regions represented by the limits of integration in Eq. (2).

$$W = \text{probe intensity difference} \frac{\int_{-p_1}^{p_2} w(\tau) d\tau}{\int_{-D_1}^{D_2} w(\tau) d\tau}, \qquad (2)$$

where $-p_1$ and p_2 are the times between the peak of the temporal window and the onset and offset of the probe, respectively, and $-D_1$, and D_2 are the times between the peak of the temporal window and the onset and offset of the entire stimulus, respectively. These times are illustrated schematically in Fig. 5 (which is based on Fig. 3 of Akeroyd and Bernstein, 2001). W in Eq. (2), then, is the probe intensity difference weighted by the ratio of the area under the temporal window occupied by the probe segment to the area under the temporal window occupied by the entire stimulus. The temporal position of the window was fixed so that the value of W was maximized. The position of the temporal window at which W was maximized was found by moving the peak of the window between the onset and offset of the probe segment in 0.1-ms steps and computing W for each peak position. Then it was assumed that the threshold intensity differences measured in the experiment corresponded to a constant "effective" intensity difference, W_0, at the output of the temporal window. Equation (2) can then be rearranged to give the predicted intensity difference at threshold:

$$\text{probe intensity difference at threshold} = W_0 \frac{\int_{-D_1}^{D_2} w(\tau) d\tau}{\int_{-p_1}^{p_2} w(\tau) d\tau}. \qquad (3)$$

The MATLAB Optimization Toolbox function "lsqnonlin" was used to estimate values of T_1, T_2, and W_0 in order to fit the temporal window to the data. The parameters were estimated in order to minimize the mean-squared error between the predictions and the data, with the mean-squared error computed using the predicted and observed values of intensity difference in units of $10 \log[(\Delta I + I)/I]$. All integrals were evaluated analytically.

The post-onset-weighting function was

$$f(t) = ae^{-t/T_a} + be^{-t/T_b} + 1, \qquad (4)$$

where t represents the time relative to the onset of the stimulus. Incorporating Eq. (4) into the fitting procedure, Eq. (3) becomes[1]

$$\text{probe intensity difference at threshold} = W_0 \frac{\int_{-D_1}^{D_2} f(\tau + D_1) w(\tau) d\tau}{\int_{-p_1}^{p_2} f(\tau + D_1) w(\tau) d\tau}. \qquad (5)$$

Note that $f(t)$ is fixed with respect to the onset of the overall stimulus while $w(\tau)$ is positioned optimally for each temporal position of the probe. When the post-onset-weighting function was included in this way, the fitting procedure amounted to estimating the parameters a, b, T_a, and T_b in addition to those of the temporal window of Eq. (1).

For all fits to the data, the percentage of variance in the actual data for which the predicted values accounted was computed as follows:

$$100 \times \left(1 - \frac{\sum (O_i - P_i)^2}{\sum (O_i - \bar{O})^2} \right) \qquad (6)$$

where O_i and P_i are the observed and predicted threshold values, respectively, and $\bar{O}$ is the mean of the observed threshold values.

The instantaneous IID function represents the presumed output of an ongoing differencing process occurring at a level of binaural interaction in the auditory system. The type of process to which the monaural intensity-difference function can be attributed is less evident. As noted by Stellmack *et al.* (2004), the two-interval monaural intensity-discrimination task depends on memory in a way that the single-interval binaural task does not, namely, a representation of the first interval of the two-interval stimulus must be stored in memory so that the difference between it and a representation of the second interval can be computed for temporally corresponding points. The present model operates on this representation of instantaneous intensity differences. In both the monaural and binaural cases, the fitting procedure considers the output of the temporal window positioned with respect to the instantaneous intensity-difference function such that the weighting of the intensity difference of the probe is maximized. However, applying the temporal window to the difference function is computationally equivalent to applying the temporal window to the individual stimuli and then computing the difference between the outputs. It is more plausible that the smoothing effects of the temporal window are due to processes occurring prior to a comparison of the two monaural intervals in memory. Given that the temporal order of the windowing and differencing procedures in the present analysis is unimportant, in the binaural conditions, windowing might be considered as occurring prior to binaural interaction as well.

TABLE I. For the set of data shown in the first column, shown are values of the parameters of the temporal window (T_1 and T_2 in ms), effective IID at the output of the temporal window (W_0 in dB), and parameters of the post-onset-weighting function (a, b, T_a, T_b, the latter two in ms). The percent of variance in the observed thresholds that the estimated parameters account for is shown in the final column. The parameter values that were allowed to vary in each nonlinear regression analysis are shown in bold type. The thresholds to which the functions were fit were expressed in units of $10 \log[(\Delta I + I)/I]$.

Data set	T_1	T_2	W_0	a	b	T_a	T_b	% accounted
1) Monaural	**4.3**	**6.8**	**4.0**					80.3
2) Interaural	4.3	6.8	**4.3**					53.6
3) Interaural	4.3	6.8	**3.2**	**47.6**	**1299.5**	**5.3**	**0.4**	93.4
4) Akeroyd and Bernstein (2001) "Both fringe"	4.1	7.4	2.7	1.8	−0.8	1.8	13.0	85.2
5) Zurek (1980)	9.8	6.6	2.1	24.9	−0.6	0.7	31	97.2

D. Quantitative analysis: Results

Because up to seven parameters were estimated to produce fits to the data (as in Akeroyd and Bernstein, 2001), numerous combinations of parameter values accounted for nearly the same proportion of variance in the actual data. As a result, independent regression analyses performed on different sets of data that appear to be similar in form can yield very different "best-fitting" function parameters. Furthermore, the nonlinear regression analysis could produce very different results for the same set of data when the analysis was initialized with different sets of starting parameters. (This variation in best-fitting model parameters did not occur when only the temporal window was fit to a set of data by estimating the best-fitting values of the three free parameters T_1, T_2, and W_0.) As a result, the test of interest is whether the best-fitting parameters estimated for one set of data can account for another set of data, that is, whether two different sets of data can be described reasonably well by the same functions. Specifically, in the present analysis, the best-fitting values of the parameters of the temporal window [described by Eq. (1)] were estimated for the monaural data and then predictions of the interaural data using the same temporal window combined with the best-fitting post-onset-weighting function [described by Eq. (4)] were evaluated.

The parameters T_1, T_2, a, b, T_a, and T_b determine the shape of the functions defined by Eqs. (1) and (4) and the shape of the threshold curves that predict the observed data in Fig. 4. The parameter W_0 effectively represents the sensitivity of the observer and simply determines the vertical position of the predicted threshold curve without changing its shape. As a result, in the analyses that follow, whenever a particular temporal window and/or post-onset-weighting function that was derived from one set of data is used in a subsequent fit to the same or another set of data, the parameter W_0 is estimated once again in order to shift the predicted threshold curve up or down to produce the best fit to the data.

As a first step in the quantitative analysis of the data, only the asymmetric temporal window was fit to the monaural data. The best-fitting values of T_1, T_2, and W_0 are shown in line 1 of Table I. The temporal window defined by these parameters accounted for 80% of the variance in the observed data.

When both the temporal window and post-onset-weighting function were included in the analysis for the monaural data (introducing four additional parameters to the fitting procedure), the resulting fit accounted for a larger percentage of the variance (82%) in the monaural data. The difference between the percentage of variance accounted for with and without the post-onset-weighting function corresponds to threshold predictions that are only about 1 dB better than those for the temporal window alone for five of the seven shortest forward-fringe durations. The parameters of the temporal window estimated without the post-onset-weighting mechanism (Table I, line 1) were used in subsequent fits to the interaural data for two reasons: (1) the inclusion of the post-onset-weighting mechanism does not improve the predicted thresholds substantially, and (2) the post-onset-weighting mechanism was posited to account for purely binaural phenomena such as the precedence effect (Zurek, 1987; Houtgast and Aoki, 1994) and, as a result, there is no apparent theoretical justification for including it in the predictions of the monaural data. [While the phenomenon of overshoot (Zwicker, 1965) involves a change in sensitivity over time, it does not seem to apply to the present situation in that lowest sensitivity resulting from overshoot occurs at stimulus onset and the effect is seen in situations involving detection of a tonal signal in a noise masker and not for noise signals.]

As Akeroyd and Bernstein (2001) observed for their own data, the temporal window alone accounted for a very low percentage of the observed variance in the present interaural data (54%; see Table I, line 2). In contrast, when the best-fitting values of the temporal window parameters (T_1 and T_2) estimated from the monaural data (Table I, line 1) were fixed and parameters for the post-onset-weighting function were estimated, the resulting functions accounted for about 93% of the variance in the interaural data (Table I, line 3). The thresholds predicted by these parameters are represented by the solid line in the upper panel of Fig. 6, plotted among the mean interaural data replotted from Fig. 4. For the present data, as Akeroyd and Bernstein (2001) observed for their own data and those of Zurek (1980), the combination of a temporal window and a post-onset-weighting mechanism can account for a large proportion of the variance in the interaural data. Furthermore, the temporal window that was

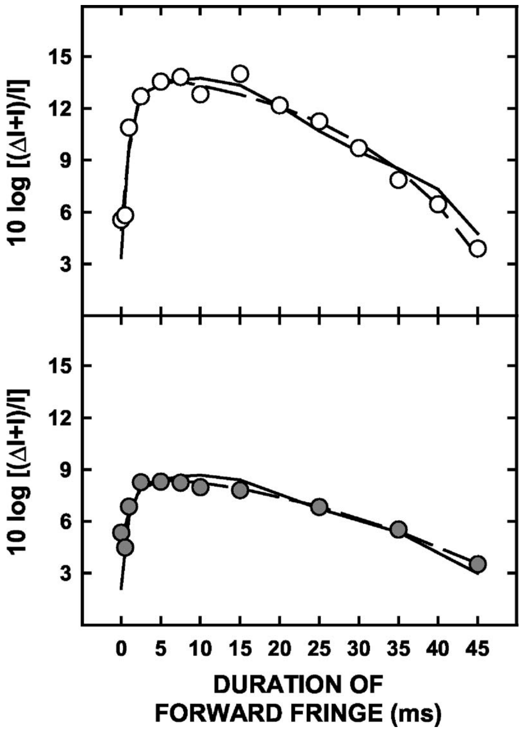

FIG. 6. The data in the upper panel are the mean interaural data replotted from Fig. 4. The data in the lower panel are the "Both-fringe" data of Akeroyd and Bernstein (2001) from their Fig. 5, panel C, open squares. The solid line in the upper panel represents thresholds predicted using the temporal window estimated from the monaural data combined with the post-onset-weighting function that produces the best fit to the interaural data. The solid line in the bottom panel shows the predictions for the data in that panel using the same temporal window and post-onset-weighting function, where the effective output of the temporal window, W_0, was allowed to vary in order to obtain the best fit. The dashed lines in both panels represent the predicted thresholds when the parameters of both the temporal window and post-onset-weighting function were allowed to vary to produce the best fit to the data in each panel.

estimated from the monaural data provides an excellent fit to the interaural data when paired with the appropriate post-onset-weighting function.

For comparison to the present data, the data of Akeroyd and Bernstein (2001) are plotted as the symbols in the lower panel of Fig. 6. [The observed threshold values were estimated from Akeroyd and Bernstein (2001), Fig. 5, panel C, open squares.] The thresholds measured by Akeroyd and Bernstein were lower than those reported in this paper, which would be expected given that they used a cued two-interval task and their adaptive procedure tracked to a lower value of percent correct. Furthermore, Akeroyd and Bernstein utilized a task involving discrimination between diotic and dichotic stimuli while the present task was a single-interval task that required discrimination between IIDs favoring the left and right ears. (As will be discussed in Sec. III, these procedural differences may limit the ability to compare thresholds obtained in the two tasks.) The temporal window and post-onset-weighting function that best fit the interaural data in Fig. 4 (defined by the parameters shown in line 3 of Table I, with W_0 free to vary) accounted for only about 58% of the variance in the IID data of Akeroyd and Bernstein (2001). The thresholds that were predicted using these function parameters are shown as the solid line in the lower panel of Fig. 6. However, when the data point for the forward-fringe duration of 0 ms is excluded, the weighting functions described by the same parameters account for over 93% of the variance in the data of Akeroyd and Bernstein. The increase in the variance accounted for is attributable to the fact that the functions used in the present fitting procedure describe large relative weight given to IIDs at stimulus onset and they cannot account well for the relative increase in threshold at stimulus onset observed in the data (noted in Sec. II B). The best-fitting parameters of the temporal window that Akeroyd and Bernstein estimated for their data are similar to the parameters estimated for the present data. The primary difference between the two fits resides in the best-fitting parameters of the post-onset-weighting function, which will be discussed in Sec. II E 2.

In all of the above-described conditions, the best-fitting parameters were estimated from the thresholds measured for the probe in the presence of diotic temporal fringes. In all cases, the parameter W_0 is the effective IID after application of the relative weights to the probe and fringe IIDs. Therefore, W_0 represents a prediction of the threshold for the corresponding probe alone condition. The value of W_0 estimated for the monaural data (4.0 dB) is very close to the mean probe alone threshold (3.8 dB), but W_0 estimated for the binaural data (3.2 dB) is somewhat higher than the observed value (1.6 dB). The value of W_0 estimated by Akeroyd and Bernstein (2001) for their IID data (2.7 dB) appears to be quite close to the observed value. It is uncertain why the estimated value of W_0 overpredicted the observed probe alone threshold for the present binaural data. One possibility raised by the results of Experiment 2 to follow is that listeners are particularly insensitive when discriminating the left-right direction of a nonzero probe IID for a brief time following stimulus onset (as opposed to discriminating a diotic from dichotic stimulus, as in Akeroyd and Bernstein, 2001). This will be discussed further in Sec. III B.

E. Discussion

1. Accounting for monaural and interaural data

The question addressed by the present experiment was whether a common set of temporal weighting functions could account for data gathered in monaural and interaural intensity-discrimination tasks in which the probe to be discriminated was preceded and followed by a temporal fringe that was fixed in intensity and, in the binaural task, diotic. The analysis showed that the double-sided exponential window that predicted the best-fitting thresholds for the monaural data also produced a very good fit to the interaural data when paired with a post-onset-weighting function that gave relatively greater weight to the binaural information at the onset of the stimulus. (The inclusion of a post-onset-weighting function did not substantially improve the predictions of the monaural data.) In other words, the relatively symmetric functions describing the monaural thresholds could be predicted well by a two-sided exponential temporal window, while it was necessary to combine a post-onset-weighting function with the same temporal window in order to account for the sharply higher thresholds after onset and the resulting asymmetry of the function describing the binaural thresholds. The fact that a common temporal window provided good predictions for both sets of data indicated that the discrimination of intensity in a brief temporal segment of a stimulus might be affected in a similar way in monaural and binaural tasks by information temporally surrounding the segment to be discriminated.

If monaural temporal resolution is limited simply by the characteristics of a temporal window that integrates intensity over time, similar estimates of the parameters of the window should be obtained from data gathered in increment- and decrement-detection tasks. However, Oxenham (1997) showed that thresholds for detection of very brief intensity increments are lower than detection thresholds for decrements of the same magnitude. Oxenham also showed that if one assumes that listeners detect increments and decrements on the basis of the output of a temporal integrator, a common two-sided exponential function does not account well for the differences. That is, estimates of the parameters of the temporal window differ when calculated separately for the two sets of data. Oxenham assumed that the time constant that determined the slope of the temporal window for times before the peak was 1.5 times the value of the time constant that determined the slope of the function after the peak. He then estimated the best-fitting equivalent rectangular duration (ERD) of the temporal window that predicted his increment- and decrement-detection data. Oxenham found that the best-fitting ERDs were many times longer for the decrement-discrimination data than for the increment-discrimination data. Oxenham's data were fit better by assuming that listeners detect increments and decrements in intensity on the basis of the positive-going slopes (the onsets of the increments and offsets of the decrements) at the output of a temporal integrator. With this assumption, Oxenham was able to account for the fact that thresholds for increment detection were lower than for decrement detection.

The preceding discussion raises two issues with respect to the present data. First, because discrimination thresholds were measured in the present experiment by simultaneously varying the (equal) magnitudes of the increments and decrements, it is possible that discrimination was performed on the basis of detection of the increments (in one interval in the monaural task and in one ear in the binaural task) while the decrements were undetectable at discrimination threshold. The same possibility exists for the data of Zurek (1980) and Akeroyd and Bernstein (2001). This issue cannot be resolved on the basis of the present data.

The second issue involves interpretation of the temporal window used in the present fitting procedure. If estimates of a temporal window differ for increment and decrement detection, the single temporal window estimated for the present discrimination task must be considered as a simple description of the data rather than of a mechanism for integrating intensity information within a single interval or channel. In other words, the temporal window measured for the discrimination task represents the net effects of the integration of intensity information in the increment and decrement of each trial, either in the two intervals of the monaural task or in both ears of the binaural task. Despite these qualifications in the interpretation of the temporal window estimated here, it remains the case that a temporal window estimated from the data in the monaural task accounts well for the interaural data when combined with an appropriate post-onset-weighting function.

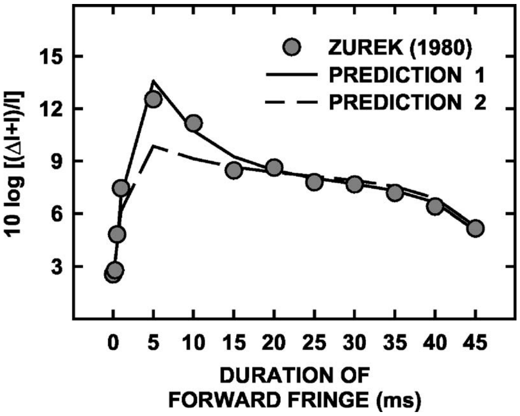

FIG. 7. Mean threshold IIDs from the two listeners of Zurek (1980) estimated from Fig. 7 of Akeroyd and Bernstein (2001). The solid curve shows predictions produced using the best-fitting weighting-function parameters estimated by Akeroyd and Bernstein. The dashed curve shows predictions generated using the same parameters but without the second term of Eq. (4). See the text for details.

2. Form of the best-fitting post-onset-weighting function

The post-onset-weighting function defined by the best-fitting parameter values estimated by Akeroyd and Bernstein (2001) for their entire body of data (their Both-fringe, Forward fringe only, and Backward fringe only data) is nonmonotonic and indicates large weight given to binaural information at the onset of the stimulus, then reduced weight (less than unity) given to information for a brief period following the onset of the stimulus after which the value of the weighting function returns to unity. For all of the post-onset-weighting functions estimated in the present paper, the functions indicate maximum weight at the onset of the stimulus, but the weight decreases monotonically to unity. In other words, the post-onset-weighting functions estimated here do not indicate a minimum in the weight applied to binaural information for a brief period following the onset of the stimulus. In fact, the parameter values estimated by Akeroyd and Bernstein only account for about 89% of the variance in their "Both-fringe" data alone (Table I, line 4), while the parameter values computed here account for over 93% of the variance in those same data (excluding the threshold for the probe at stimulus onset from the data for both fits, as previously noted in Sec. II D). Likewise, the parameter values estimated by Akeroyd and Bernstein account for only about 77% of the variance in the interaural data of the present experiment.

In their analysis of Zurek's (1980) data, Akeroyd and Bernstein (2001) found, as for their own data, that the parameters of the best-fitting post-onset-weighting function (Table I, line 5) also describe a nonmonotonic function like that described earlier. The thresholds predicted using these parameter values are plotted as the solid line in Fig. 7. The data points in Fig. 7 are the average data of Zurek estimated from Fig. 7 of Akeroyd and Bernstein (2001). It can be seen that the predicted thresholds provide a very good fit to the data.

The nonmonotonicity in the post-onset-weighting function defined by the parameters in Table I, line 5 can be removed by eliminating the second term in the function [i.e., setting b in Eq. (4) to zero]. The result is a post-onset-weighting function that is simply an exponentially decreasing function. The predicted thresholds using this post-onset-weighting function are shown by the dashed line in Fig. 7. By comparing the solid and dashed lines in Fig. 7, it can be seen that the nonmonotonicity in the post-onset-weighting function produces large changes in threshold predictions (increases) for probes with onsets shortly after the overall stimulus onset. This nonmonotonicity is necessary in order to predict the sharp peak in the thresholds of Zurek's listeners for a forward-fringe duration of 5 ms. The thresholds reported by Akeroyd and Bernstein in their "Both-fringe" conditions do not exhibit as large a peak at 5 ms relative to surrounding thresholds (lower panel of Fig. 6) and, accordingly, the data could be predicted well by a post-onset-weighting function that decreases monotonically, as was the case for the present data. Thus the common characteristic of the best-fitting post-onset-weighting functions for all of the data considered here describes a maximum weight at onset followed by a rapid decrease immediately after onset. Whether the best-fitting function reaches a minimum after onset or decreases monotonically throughout the stimulus appears to depend on individual differences in sensitivity of the listeners to probe IID shortly after stimulus onset.

The best-fitting post-onset weighting functions for the present interaural data and those of Zurek (1980) are the sum of decaying exponentials such that one with a short time constant is weighted very heavily relative to the other with a longer time constant (see Table I, lines 3 and 5). In other words, these post-onset-weighting functions give very large relative weight to the IID at the onset of the stimulus and the relative weight decays very rapidly after stimulus onset. The best-fitting parameters represent very fast and large changes in sensitivity that may be biologically unrealistic, suggesting that the functions derived here may not correspond directly to underlying biological processes.

One factor that led to a very large peak value for the post-onset-weighting function is that, in the fits to the interaural data of the present paper, the parameters of the temporal window were fixed at the best-fitting values determined from the monaural data. If the parameters of the temporal window were allowed to vary as well, the peak value of the best-fitting post-onset-weighting function is similar to that obtained for Zurek's (1980) data. In all cases, a large peak value in the post-onset-weighting function (or, more accurately, a large difference between the initial value of the post-onset-weighting function and the value of the function after several ms) is necessary to account for the relatively large difference between thresholds measured for probes at the stimulus onset (forward fringe duration=0 ms) and thresholds measured with forward fringe durations between about 2.5 and 20 ms (as illustrated in Fig. 7). When the difference between minimum and maximum thresholds is smaller [as in the data of Akeroyd and Bernstein (2001)], the best-fitting post-onset-weighting function has a smaller peak value. Experiment 2 explores the possibility that the range of thresholds across forward fringe durations may be related to the specific experimental procedure.

III. EXPERIMENT 2: COMPARISON OF PROCEDURES

The three sets of data considered in this paper were collected using different procedures. In this section, it will be shown that some of the differences between the data that were compared earlier in this paper can be attributed to these procedural differences.

In the interaural task of Experiment 1, a single-interval procedure was used in which an intensity increment occurred at one ear (chosen randomly on each trial) while a decrement was simultaneously presented to the other ear. The listener's task was to identify which ear the resulting nonzero IID favored, a left-right discrimination task. Zurek (1980) used a three-interval procedure in which the signal interval presented an intensity increment to one ear and a simultaneous decrement to the other while in the nonsignal intervals the increment and decrement were presented to opposite ears relative to the signal. Thus, Zurek's task also was a left-right task in which the signal carried an IID favoring the right ear and the nonsignals carried an IID favoring the left ear.

Akeroyd and Bernstein (2001) used a four-interval task that essentially amounts to a two-interval forced-choice task with cue (nonsignal) intervals added to the beginning and end of each trial. The signal, which could appear in either the second or third interval of a trial, contained an intensity increment to one ear and a simultaneous decrement to the other. (The ears to which the increment and decrement were presented presumably were held constant.) The remaining intervals of each trial were diotic. If one arbitrarily assumes that the IID in the signal interval favored the right ear, this task can be described as a center-right task, one in which the listener discriminates a dichotic stimulus from diotic stimuli. An added feature of the Akeroyd and Bernstein procedure was the fact that the nonsignal intervals also carried diotic increments or decrements (determined randomly for each interval) at the same temporal position as the signal nonzero IID that was designed to minimize monaural, energy-based cues to detection of the dichotic stimulus. This experiment examines the relevance of the primary differences between the left-right and center-right procedures as well as the effects of the diotic increment or decrement in the nonsignal intervals of Akeroyd and Bernstein.

A. Methods

Thresholds were measured in three different conditions, all of which were two-interval, forced-choice tasks. In the left-right condition, designed to mimic the task of Zurek (1980), the signal interval contained an increment to the right ear and a decrement to the left ear while in the nonsignal interval the ears of presentation of the increment and decrement were reversed. In the center-right condition, as in the experiment of Akeroyd and Bernstein (2001), the signal interval contained an increment to the right ear and a decrement to the left ear while the nonsignal interval contained a diotic increment or decrement (chosen randomly on each trial) at the same temporal position as the signal nonzero IID. In a third condition, "flat-right," the signal interval contained an increment to the right ear and a decrement to the left while the nonsignal contained no increment or decrement. While the diotic, nonsignal increment or decrement of the center-right condition, in theory, minimizes a potential monaural detection cue, the flat-right condition seeks to establish whether listeners utilize this cue.

In Experiment 1, the stimulus spectrum level during the decrement was held constant across trials and the spectrum levels during the fringe and increment were varied as dictated by the adaptive procedure. In this experiment, the spectrum level of the fringe was held constant (at 30 dB) and the spectrum levels during the increment and decrement were varied according to the adaptive procedure. A three-down, one-up adaptive procedure that tracked to the 79.4% correct level was used (Levitt, 1971). The increments and decrements in each trial were equal in magnitude in units of $10\log[(\Delta I+I)/I]$. The increments and decrements were varied adaptively in those units as well. The initial step size was set to 1 dB and was reduced to 0.5 dB after four reversals. A block of trials was terminated after 12 reversals and the mean increment/decrement size (in dB) at the final eight reversals was taken as threshold. Four blocks of trials were run in each condition and the four resulting threshold estimates were averaged to produce the final threshold for that condition. Thresholds were measured for forward fringe durations of 0, 5, 25, and 45 ms.

All remaining details of stimulus generation and threshold estimation were the same as those of Experiment 1. As in Experiment 1, the fine structures of the noises were identical at the two ears. [The noise bursts used by Zurek (1980) were interaurally uncorrelated while the noise bursts of Akeroyd and Bernstein (2001) and the present study were diotic. The effects of this difference are not examined here.] Only listeners S1 and S2 (the third and first authors, respectively) ran these conditions.

B. Results and discussion

In Fig. 8, thresholds are plotted in terms of the change in IID across intervals in units of $10\log[(\Delta I+I)/I]$ as a function of forward-fringe duration for the flat-right (circles), center-right (squares), and left-right (triangle) conditions. In other words, the magnitude of the IID within each interval of the left-right task was half the value plotted in the figure. For example, for a left-right threshold plotted as $\Delta\text{IID}=18$ dB in the figure, the IID at threshold was +9 dB in one interval and −9 dB in the other. The data for the two listeners were very similar so only the means are shown in Fig. 8.

There is little or no difference between the data of the flat-right and center-right conditions (circles and squares in Fig. 8). This suggests that these listeners generally made no use of the available monaural cues in the flat-right task.

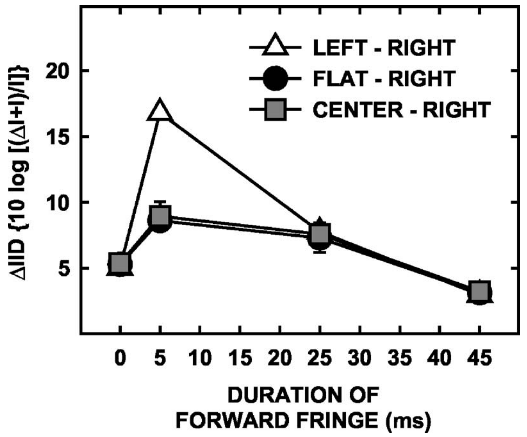

FIG. 8. Mean thresholds (of two listeners) plotted as the change in IID across intervals as a function of forward-fringe duration for the flat-right (circles), center-right (squares), and left-right (triangles) conditions of Experiment 2.

The thresholds in the flat-right, center-right, and left-right conditions (all three symbol types in Fig. 8) are in perfect agreement for forward-fringe durations of 0, 25, and 45 ms. This suggests that performance in these conditions was determined by the magnitude of the change in IID across intervals. For a forward-fringe duration of 5 ms, the left-right thresholds are substantially larger than would be predicted from the flat-right and center-right thresholds assuming that listeners' performance is determined by the magnitude of the change in IID across intervals. As a result, across forward-fringe durations, sensitivity appears to be lower for probe IIDs just after stimulus onset in the left-right task relative to the flat-right and center-right conditions. The larger peak in the left-right function is reminiscent of that shown for Zurek's data in Fig. 7. It may be the case that the effects of procedural differences are the source of the apparent relative insensitivity of Zurek's listeners to probe IIDs shortly after stimulus onset. Dr. Zurek (private communication) suggests that an important difference between the left-right task and the other two tasks is that the left-right task requires discrimination of the direction of IID in the two intervals while the center-right and flat-right tasks can be performed by a processor that discriminates diotic from dichotic stimuli. In this context, the differences between the post-onset-weighting functions computed in Experiment 1 for data gathered with left-right and center-right procedures may reflect a greater loss in sensitivity to the (left-right) direction of a nonzero IID than to the difference between diotic and dichotic stimuli for a brief time period following stimulus onset. Given the differences between the data of the left-right condition and those of the center-right and flat-right conditions and the apparent differences in listener strategies that they represent, it is probably unreasonable to expect that the data gathered with the different procedures can be predicted by common weighting functions. The fact that the best-fitting parameter values for the left-right data of Experiment 1 accounted for the center-right data of Akeroyd and Bernstein (2001) reasonably well may have been merely fortuitous.

Recall that the estimate of W_0 obtained for the binaural data of Experiment 1 over-predicted the probe-alone threshold, while the estimate of W_0 for the IID data of Akeroyd and

Bernstein (2001) was very close to their observed probe-alone threshold. As suggested earlier, perhaps decreased sensitivity to the direction of IID following stimulus onset contributed to drive thresholds higher in the left-right conditions of Experiment 1 in which a fringe was present. This factor was not present in the center-right discrimination task of Akeroyd and Bernstein (2001).

Another difference between the procedures that produced the data considered in this paper that might be expected to have differential effects on the data is related to the number of intervals. In Experiment 1 of this paper, a single-interval binaural task was used while Zurek (1980) and Akeroyd and Bernstein (2001) used multi-interval tasks. As a result, the stimuli of the latter two studies and those in Experiment 2 may have produced a perception of movement across intervals that was not present in the single-interval task. (The single-interval thresholds of Experiment 1 are somewhat larger than the two-interval left-right thresholds of Experiment 2.) Yost *et al.* (1974) showed that the introduction of a movement cue in a two-interval lateralization task can lead to results that are not directly predictable from data gathered with a single-interval procedure. The absence of a movement cue in the single-interval binaural task contributes to its utility in comparisons to the two-interval monaural intensity-discrimination task.

IV. CONCLUSIONS

(1) The function describing mean monaural intensity-discrimination thresholds for a 5-ms probe in a 50-ms stimulus as a function of forward-fringe duration was a roughly symmetrical, inverted U with lowest thresholds when the probe segment was near the onset or offset of the overall stimulus. The function describing interaural intensity-discrimination thresholds for a probe of the same duration in a diotic fringe was more asymmetrical with highest thresholds measured when the probe segment occurred shortly after the onset of the overall stimulus. A temporal window fitted to the monaural intensity-discrimination data provides a very good fit to the IID-discrimination data when combined with a post-onset-weighting function that produces maximum sensitivity to binaural information at the stimulus onset. That is, the symmetrical monaural data can be predicted very well through a model incorporating a temporal window alone while predictions of the more asymmetrical binaural data require both the temporal window and post-onset-weighting function.

(2) When an individual listener is particularly insensitive to binaural information shortly after stimulus onset (as in Zurek, 1980), the post-onset-weighting function that provides the best fit to the data contains a nonmonotonicity with a minimum after stimulus onset.

(3) Thresholds measured as a function of forward-fringe duration with center-right and left-right procedures differ in form to the extent that it is probably inappropriate to attempt to fit both sets of data with common weighting functions. Thresholds in the two tasks for forward-fringe durations of 0, 25, and 45 ms are consistent with the notion of listeners performing the task on the basis of cues determined by the difference in IID between intervals, while the change in IID across intervals could not account for the data in both center-right and left-right tasks for a forward-fringe duration of 5 ms. Left-right thresholds were larger than center-right thresholds, suggesting that differences between the best-fitting parameters of the post-onset-weighting mechanisms in the two cases may represent a decrease in directional (signed-IID) sensitivity for a brief time following stimulus onset in the left-right task.

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[1] Equation (5) also was used in the fitting procedure of Akeroyd and Bernstein (2001), as the present authors have confirmed with Dr. Akeroyd (private communication).

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