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A population study of the precedence effect

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Abstract

Data are reported from a population of untrained individuals under lag- and single-click conditions in a discrimination suppression precedence-effect task. The cue to be discriminated was an interaural level-difference (ILD). Each of 91 observers completed 10 runs in a two-interval forced-choice design under a lag-click condition and three runs under a single-click condition. Stimuli were 125-μs rectangular pulses and the interclick interval was 2 ms. Observers were randomly assigned to three groups of approximately 30. Each group was then tested at one stimulus intensity (43, 58, or 73 dB). Mean threshold within each group was greater than 15 dB for the lag-click condition and 6 dB for the single-click condition, although there was substantial interobserver variability. In contrast to [J. Acoust. Soc. Am. 114 (2003) 420] who reported a strong effect of intensity on lag-click ITD discrimination, no effect of intensity was observed on lag-click ILD thresholds. Analysis of over 50,000 near-threshold trials from 302 observers pooled across studies showed a spatial asymmetry in response patterns and a small, but statistically significant effect of gender. A model is proposed which shows that decay of sensory memory and increases in auditory filter bandwidths with intensity may predict the different findings for ILD versus ITD lag-click thresholds.

Keywords: Discrimination suppression; Echo; Precedence; Population

1. Introduction

The precedence effect in sound localization has been the topic of extensive study in the hearing sciences for over half a century (Wallach et al., 1949; Haas, 1949). In spite of an extensive history of theoretical (Lindemann, 1986a,b; Zurek, 1987; Zurek and Saberi, 2003; Saberi and Petrosyan, 2004; Freyman et al., 1997, 1998), neurophysiological (Cranford and Oberholtzer, 1976; Yin and Litovsky, 1995; Mickey and Middlebrooks, 2001), applied (Blauert, 1989; Muncey et al., 1953; Clifton et al., 2002), and even clinical (Hochster and Kelly, 1981; Ashmead et al., 1998a,b; Ashmead and Wall, 1999) research, the mechanisms that underlie onset dominance are not well understood. For reviews see Gardner (1968), Zurek (1987), Yost and Guzman (1996), and Litovsky et al. (1999).

Current views consider the precedence effect to involve a number of different onset-dominance phenomena. These include high-level processes that invoke long time-constants in the order of several seconds (Clifton, 1987; Clifton and Freyman, 1989; Clifton et al., 2002; Freyman et al., 1991; Yost et al., 1997; Franssen, 1960) as well as low-level non-cortical processes such as binaural adaptation (Hafter et al., 1983, 1988; Hafter and Dye, 1983; Saberi, 1996) and lateral inhibition (Lindemann, 1986a,b). The diversity of findings related to onset dominance has necessitated multiple approaches to its study (Blauert, 1997; Djelani and Blauert, 2001; Perrott et al., 1989). The reader is referred to Blauert and Col (1991) for a discussion of irregularities in defining the precedence effect.

The current study uses a population approach to the study of the precedence effect in which we examine discrimination suppression thresholds from a large number of untrained listeners. It was partially motivated by findings from Saberi and Antonio (2003) who investigated population parameters in a study of ITD cues

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in a precedence-effect task. Saberi and Antonio reported that: (1) large inter- and intraobserver variability is seen in lag-click threshold estimation, (2) lag-click adaptive-track trajectories are unstable and nonmonotonic consistent with a dual-cue percept, (3) stimulus intensity significantly affected lag-click but not single-click thresholds, and (4) the best naïve listener performed poorer than experienced observers.

In the current study, we examined population ILD thresholds for two-transient dichotic stimuli. The population was composed of experimentally naïve young college students. The population approach allows the establishment of a databank and a statistical baseline for a task that has produced large threshold variability across studies, as well as the ability to compare population ILD-thresholds with population ITD-thresholds from Saberi and Antonio (2003). Pooling data from the 302 observers across the two studies has, in addition, allowed statistically meaningful comparison of male to female performance, as well as an examination of other population measures such as effect of handedness (left- versus right-handed observers), and spatial bias. In addition, we examined the effects of stimulus intensity on lag-click ILD population thresholds, and surprisingly found results in contrast to those we have reported for ITD cues. Finally, a cross-correlation model is developed to account for the observed differences of stimulus intensity on ITD and ILD lag-click thresholds.

2. ILD thresholds for single and lag clicks as a function of stimulus intensity

2.1. Materials and methods

2.1.1. Stimuli

Stimuli were 125-μs rectangular pulses generated in a Dell PC (OptiPlex GX1) and presented through 16-bit digital-to-analog converters (Sound Blaster Live, Milpitas, CA) at a sampling rate of 40 kHz and were low-pass filtered at 20 kHz. Observers listened to stimuli over Sony (MDR-V1) headphones in an acoustically isolated steel chamber (Industrial Acoustics Company, with interior dimensions of $1.8 \times 1.9 \times 2$ m). The level of a single pulse was calibrated to 43, 58, or 73 dB (A weighted; Slow time average), depending on the experimental condition, using a 6cc coupler, 0.5 in. microphone (Brüel & Kjær, Model 4189) and a modular precision sound analyzer (Brüel & Kjær, Type 2260). [1] Measurements of the headphone outputs, using a 6cc coupler, 0.5 in. microphone (B & K), a conditioning amplifier (Nexus, B & K), and an analog-to-digital converter (Sound Blaster) showed that the pulse spectrum was linear for the three intensities tested (43, 58, and 73 dB). The timing between pulses and between channels, as well as the level between channels was checked for accuracy at each SPL with a dual-channel digital storage oscilloscope (Tektronix, Model TDS210) and the microphone assembly described above. Measurements showed that interclick interval for a two-click train with an ICI of 2 ms, measured at the *output* of the headphones at the three stimulus intensities was unaffected by the chosen intensities and the headphone transfer function.

2.1.2. Observers

Observers were untrained young college students (ages 18–22) who were recruited from campus advertisements and were paid an hourly wage for their participation. They were randomly assigned into one of three groups of approximately 30 individuals per group. We selected this group size because it provided sufficient statistical power for estimation of population parameters (Pitman, 1993; Hays, 1981). In addition to an hourly wage, observers were told that the individual with the lowest overall threshold within their respective group (of approximately 30) would receive a financial bonus. All observers had normal hearing based on self-report. Each observer was asked if s/he had a head cold, and if so, was rescheduled.

2.1.3. Single-click condition

Observers listened to the stimuli in an initial pilot run in the presence of the experimenter for several trials until the experimenter was satisfied that s/he understood the task. This short pilot run was then terminated, usually within 15 trials, and the experiment was started after the experimenter left the chamber. Each run consisted of 50 trials in an adaptive 2-down 1-up design, which tracks the 70.7% correct-response threshold (Wetherill and Levitt, 1965; Levitt, 1971). On the first interval of each trial of the single-click condition, the ILD favored one randomly selected ear (higher level at that ear), and in the second interval, it favored the other ear by the same ILD. The task was to specify if the two intracranial sound images in the two intervals of the trial were heard left then right, or right then left. The observer would then press either a left or a right key to respond (left-key response meant that they perceived the sound orders as right to left). Visual feedback was provided after each trial in two forms. First, the observer was informed if s/he was correct (e.g., if the order of presentation of the stimuli in the two intervals were ILD favoring left ear then right ear and the observer responded by pressing the right key, the trial was recorded as correct). Second, in an image window on the screen, the adaptive track for

[1] For comparison, a continuous 10-Hz train of clicks had intensities of 51, 66, and 81 dB, and at 100-Hz these intensities were 60, 75, and 90 dB. At the highest stimulus intensity, the level of a single pulse at the fast (125 ms) time-average setting was 79 dB, at an impulse setting was 84 dB, and at peak-amplitude setting was 114 dB.

the current run was displayed which included the ILD values up to the current trial in a graph (i.e., a plot of the trial number vs. ILD value). Observers were instructed to use this trial-by-trial updated graph and the feedback to try to achieve the lowest possible score. The initial ILD in the adaptive run was 40 dB (20 dB in each interval of the 2IFC design). Two correct responses led to a reduction of ILD by 4 dB up to the fourth reversal, and 1 dB thereafter. The dB changes were achieved by a simultaneous increase of level in one ear by half the stepsize, and decrease of level in the other ear by the same amount. An incorrect response led to an increase in the ILD by the stepsize. Lowest and highest possible values of ILD within an interval were 0 and 40 dB, and if the adaptive track required values outside this range, they were corrected to these floor and ceiling values. In all cases, threshold was estimated as the average of the stimulus values at track reversal points, after the third or fourth reversal, to ensure an even number of reversal used in calculation of threshold. Usually, six or eight reversals went into the calculation of each threshold value.

2.1.4. Lag-click condition

Each observer completed a total of 13 runs. The first two runs, as well as the last run, measured threshold for a single dichotic click as described in the previous section. In runs 3–12, the stimulus in each interval of a trial consisted of two clicks, the first representing the lead diotic event and the second representing the lag dichotic event. The ICI was 2 ms. This value has been shown to produce a strong precedence effect for impulsive sounds (Wallach et al., 1949; Zurek, 1980; Zurek and Saberi, 2003; Saberi and Antonio, 2003). The ILD of the lead click was always zero, and thus carried no information for resolving the task. The lag click had an ILD that varied according to the adaptive rules described above. All other stimulus parameters and procedures were the same as that described for the single-click condition. The protocol for experiments on human subjects were approved by the University of California's Institutional Review Board.

2.2. Results

Left panels of Fig. 1 show results from this experiment. Data from 91 observers are shown with 30, 29, and 32 observers per group for each stimulus intensity from left to right, respectively (43, 58, and 73 dB). Upper-left panel shows ILD thresholds for the lag-click condition, and the bottom-left panel for the single-click condition. Dashed vertical lines show the population mean threshold for each condition. Each of the three histograms of the top-left panel is based on approximately 300 threshold estimates (10 per observer), and each histogram in the bottom-left panel shows about 90

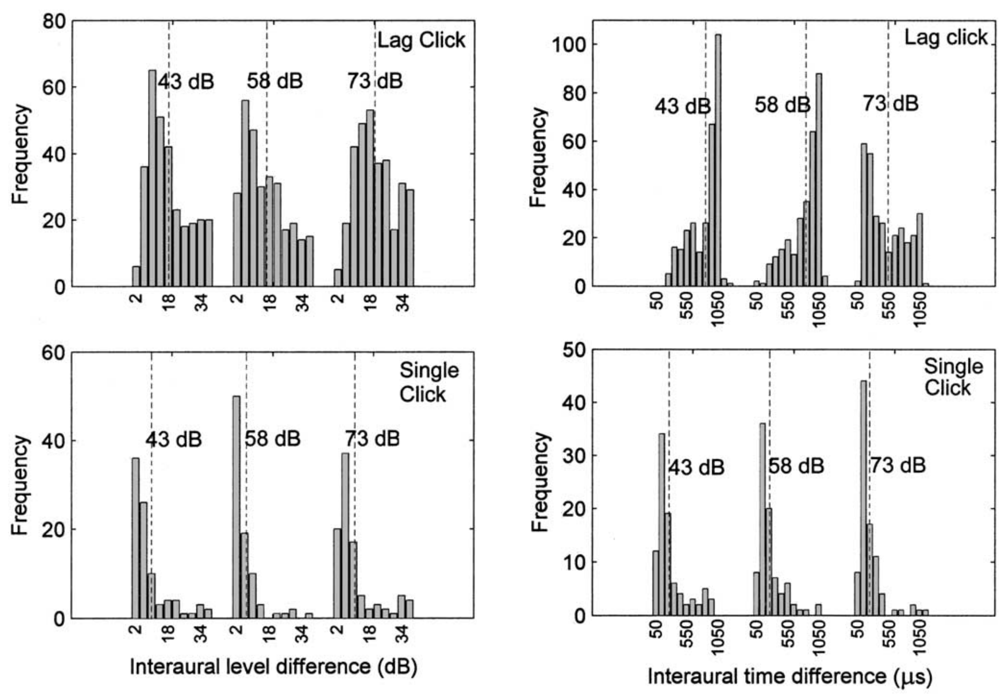

Fig. 1. Histograms of ILD thresholds (left panels) in single- and lag-click conditions as a function of stimulus intensity. Data for the three stimulus intensities are shown within the same panel for comparison, arranged from the lowest to highest intensities (43, 58, and 73 dB). Dashed vertical lines represent distribution means. Each histogram for each intensity level is based on approximately 300 threshold estimates in the top panel and 90 estimates in the bottom panel. Data are from 91 observers. Right panels show results from Saberi and Antonio (2003). See text for details.

threshold estimates (3 per observer). The bin width is 4 dB, and values at center of bins are shown along the abscissa for selected bins. The ordinate shows the number of thresholds that fall within each bin. The mean population ILD threshold for the three stimulus intensities of 43, 58, and 73 dB are 10.1, 6.7, and 10.5 dB for the single-click condition, and 18.4, 16.8, and 20.4 dB for the lag-click condition, respectively. The *modes* are 2, 2, and 6 dB (single click), and 10, 6, and 18 dB (lag click). The standard deviations are 9.8, 8.2, and 9.9 (single click), and 10.0, 10.5, and 9.6 dB (lag click).

For comparison, the right panels of Fig. 1 show population ITD thresholds from Saberi and Antonio (2003) under experimental conditions identical to the current study, except that the cue to be detected was an ITD instead of an ILD. Observers in Saberi and Antonio (2003) were different than those from the current study. No significant effect of stimulus intensity was observed on either lag- or single-click ILD thresholds. This result is in contrast to ITD thresholds (right panels) reported by Saberi and Antonio (2003) which show a clear effect of stimulus intensity for lag-click, but not single-click thresholds. Furthermore, the strength of precedence, that is the change in threshold resulting from discrimination suppression seems greater for the ITD cue than for the ILD cue, except at the highest intensity. A non-parametric Kolmogorov–Smirnov test on the difference between single- and lag-click threshold distributions was significant at the three intensities tested: $D_{300,90} = 0.5856$, $p < 0.001$, $D_{290,87} = 0.5632$, $p < 0.001$, and $D_{320,96} = 0.6010$, $p < 0.001$ for intensities of 43, 58, and 73 dB, respectively. This test was also significant for the ITD-based distributions: $D_{300,90} = 0.7289$, $p < 0.001$, $D_{290,87} = 0.7632$, $p < 0.001$, and $D_{300,90} = 0.4233$, $p < 0.001$ for intensities of 43, 58, and 73 dB, respectively. Note that D values are greater for the ITD conditions at the 43- and 58-dB levels, but not for the 73-dB level. This suggests that a greater mean

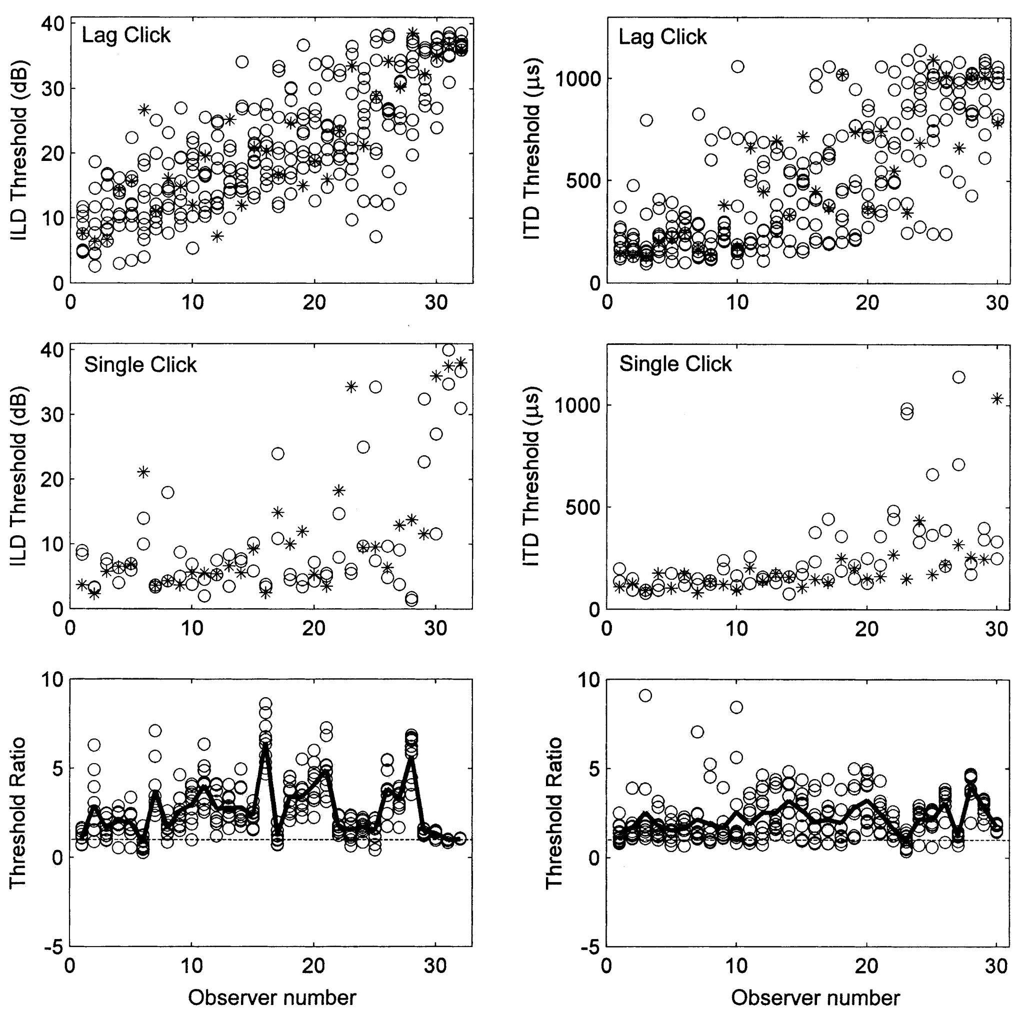

Fig. 2. Left panels show single-run ILD thresholds for 32 observers from the lag- and single-click conditions (top and middle panels) as well as the ratio of lag-click thresholds to the mean of single-click thresholds for each observer (bottom panel). These data correspond to the 73-dB condition shown in the left panels of Fig. 1. Each circle or asterisk represents one threshold estimate from a 50-trial run. The asterisks are the final run for each observer at each condition (lag or single click). Right panels show results from Saberi and Antonio (2003).

discrimination suppression is observed for the lower level ITD conditions compared to ILD conditions. However, this trend is reversed at the highest intensity of 73 dB where greater discrimination suppression is observed for the ILD condition. Furthermore, comparing *D* statistics across intensities shows that mean discrimination suppression is more stable as a function of intensity for the ILDs compared to ITDs.

Fig. 2 shows intra- and interobserver variability for ILD thresholds (left panels) from the current study and for ITD thresholds (right panels) from Saberi and Antonio (2003) at the highest stimulus intensity tested (73 dB). Upper panels show data from lag-click conditions, middle panels from single-click conditions, and the bottom panels show the ratio of lag-to-single click thresholds. For this last measure, we used the mean single-click threshold from three runs and divided each of ten lag-click thresholds for each observer by this mean. The threshold ratio represents the strength of precedence, with a ratio of unity (dashed horizontal line) representing equal effectiveness of the single and lag clicks. Observer numbers are arranged along the abscissa according to increasing mean lag-click thresholds (e.g., observer #1 is the same individual in all panels of the left column). Each symbol in each panel represents a threshold estimate from a 50-trial run. The asterisks in each panel show the threshold estimates for the last run of each condition. These are the 12th and 13th runs of the experiment for the lag- and single-click conditions respectively. Note that the last run for each condition and observer sometimes produces the lowest threshold, sometimes the highest and sometimes middle values. This suggests that within-observer variability is not simply a result of learning during the experiment. Also note that thresholds appear scattered throughout the range of interaural delays, indicating substantial interobserver variability.

The correlation coefficient between the mean lag- and single click conditions for the ILD case is $r = 0.70$ (i.e., correlation between 32 mean lag-click and 32 mean single-click thresholds) and for the ITD case it is $r = 0.74$, indicating a slightly less intra-observer variance in discrimination suppression for the ITD condition. The threshold ratio in the bottom panels show the large variability in the strength of precedence across observers. For the ILD condition (bottom-left panel) mean threshold ratios (solid line) ranged from 0.86 to 6.46, with a mean ratio of 2.62 across 32 observers. For the ITD condition, threshold ratios ranged from 0.98 to 4.01, with a mean of 2.2. Note also the greater variability of mean threshold ratios (solid lines) in the ILD compared to the ITD condition ($\sigma_{\mathrm{ILD}} = 1.39$ compared to $\sigma_{\mathrm{ITD}} = 0.67$). Mean threshold ratios for some observers are near or even smaller than unity, suggesting an absence of precedence effect. These subjects include not only those that generally perform poorly in all tasks (e.g., observers 31 and 32 in the ILD condition), but also those that are among the best performing observers (ILD observers 1 and 6). Some ITD observers also show weak or no precedence (observers 1, 2, 4–6, 23, 27) although the best ITD subjects appear to always produce threshold ratios of at least 1.5.

3. Population parameters: gender, handedness, and spatial bias

Data from 302 untrained observers pooled across studies were used in analyzing the effects of gender, handedness, and spatial bias on lag-click thresholds. [2] Of these observers, the majority were female (75% or 225 individuals) because more females had responded to our campus advertisements. Since both populations are fairly large, the difference in population size is inconsequential to our analysis. In addition to gender, the population was examined for effects of handedness (12% of all observers were left-handed, i.e., 36 individuals). To compare thresholds for males versus females, we transformed an individual's thresholds within each group of observers to *z*-scores and pooled these values from all males across all groups (ILD and ITD thresholds) as one category, and all *z*-values from all females in a second category. Fig. 3 shows histograms of normalized thresholds for females (top panels) and males (middle panels). Vertical dashed lines correspond to the distribution means. For the lag-click condition, the mean threshold for females was 0.236 σ units higher than that for males. For the single-click condition, the mean threshold for females was 0.302 σ units higher than that for males. On average, the female population showed about a quarter of standard deviation higher mean threshold. Bottom-left panel shows Gaussian density functions with means and variances corresponding to those from the male and female lag-click distributions, with means of −0.151 and +0.085, respectively (lag-click distributions are approximately normal based on a Kolmogorov–Smirnov test of normality). A *t* test of the difference between the means of the distribution of lag-click thresholds (histograms in left column) from male and female observers was significant [$t(300) = 1.78$, $p < 0.05$]. The histograms in the right column, however, show that the single-click distributions are not normal (positively skewed). To facilitate visual inspection only, we have plotted modified gamma density functions in the bottom-right panel with peaks corresponding to the means of the histograms (−0.214 for males and +0.088 for females). A Kolmogorov–Smirnov test showed that the two distributions of single-click thresholds (male vs.

[2] Section 3 shows data from 302 observers who participated in experiments from the current study, from Saberi and Antonio (2003), as well as observers who ran in preliminary conditions not shown here.

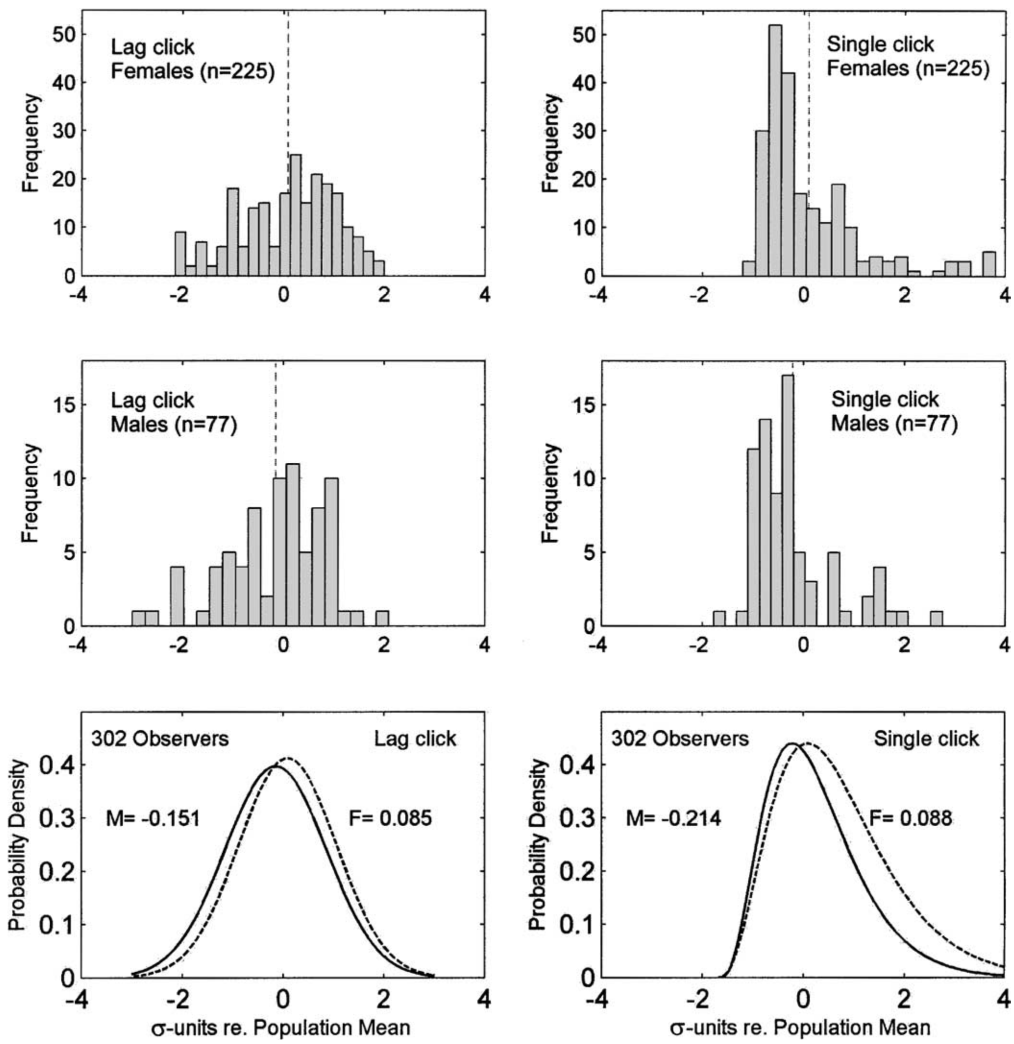

Fig. 3. Histograms of normalized thresholds from females (top row) and males (middle row). Dashed vertical lines correspond to the distribution mean in each panel. Left panels show data from the lag-click condition and right panels from the single-click condition. Bottom-left panel shows Gaussian density functions with means (M, males; F, females) and variances corresponding to those from the histograms in the left panel. Bottom-right panel shows modified gamma density functions with peaks corresponding to means of the histogram distributions in the right panels (see text).

female) are significantly different ($D_{225,77} = 0.1975$, $p < 0.05$). The cause of this difference in mean threshold between females and males is not clear, however, it is not specific to the precedence effect since it is observed for both single- and lag-click conditions, and has also been previously reported for ITD and ILD discrimination in noiseburst stimuli (Langford, 1994).

Previous work has shown a spatial asymmetry for onset dominance (Clifton and Freyman, 1989; Grantham, 1996; Freyman et al., 1997). Lag clicks that are presented from the right side of an observer appear to be heard as more distinct. To investigate possible spatial asymmetries within our population, we examined performance both as a function of handedness and the direction (sign) of the lag-click cue. In units of standard deviation, the difference between left- and right-handed observers was quite small; the left-handed observers showed a mildly higher mean threshold than right-handed observers by 0.109 σ for the lag-click condition, and 0.198 σ for the single-click condition. These differences are not significant. To examine spatial bias, we compared performance for stimuli with an interaural cue favoring the left ear to those favoring the right ear. A trial-by-trial inspection of left–right responses across all observers, irrespective of handedness, revealed interesting patterns. We analyzed a large number of near-threshold trials, i.e., excluding the first 20 trials of each run. Of 54,000 near-threshold trials, 27,171 were stimuli with an interaural cue leading to the right, i.e., a posteriori probabilities of 0.503 and 0.497. However, the probability of a correct response given a right-leading cue, $P(c|R)$, was significantly higher than that corresponding to a left-leading cue. When the cue to be detected was an ITD, $P(c|R)$–$P(c|L)$ was +8%, +10%, and +11% for the three stimulus intensities of 73, 58, and 43 dB, respectively. When the cue to be detected was an ILD, $P(c|R)$–$P(c|L)$ was +5%, +10%, and +11%

for the three stimulus intensities of 73, 58, and 43 dB, respectively. This pattern, which was observed in both male and female populations, indicates either a bias in population responses toward the right-ear leading signal, or an asymmetry in perception of interaural cues. Note also that there appears to be a trend of increasing spatial bias with stimulus intensity for both the ILD and ITD conditions. The reason for this trend is not clear. No significant relationship between handedness and spatial bias was observed.

4. Discussion

4.1. Inter- and intraobserver variability

A number of previous studies have reported considerable interobserver variability for ITD or ILD discrimination tasks. Such variability was initially observed in some studies by McFadden and his colleagues (McFadden et al., 1971; Jeffress and McFadden, 1971; McFadden et al., 1972; McFadden and Sharpley, 1972). McFadden et al. (1973) examined interobserver variability in a population of 73 individuals and reported that one category of observers were significantly more sensitive to ITDs and a second category to ILDs. Approximately 13% of observers (10 out of 73) were categorized as ITD-sensitive, 42% as ILD-sensitive (31 observers), with the contingency that an observer must be at least 10% more sensitive to one cue compared to the other, to be categorized as cue-sensitive. McFadden et al. (1973), however, did not observe sex differences in cue sensitivity. These findings suggest that one may observe categorically different results if a binaural task is based exclusively on small-sample statistics, and points to the importance of population characteristics in considering binaural phenomena.

An important feature of the current data, as well, is the large interobserver variability in threshold estimates. As shown in Fig. 2, observers who produced low lag-click thresholds also generally produced low single-click thresholds, although this is not always the case (compare observers 16 and 17 in the ILD condition in bottom-left panel of Fig. 2). The correlation coefficient between the mean lag- and single-click thresholds was 0.70 for ILDs and 0.74 for ITDs. In the ITD condition, some observers with relatively low lag- and single-click thresholds produced occasional outlier high-threshold runs in lag-click conditions. These include, for example, observers 2, 3, 7, 9, and 10. These extreme outliers are not observed in the lag-click ILD condition, and did not necessarily occur at the beginning of the runs, as there was no set pattern to their occurrence.

An examination of a large number of adaptive tracks showed that ITD tracks were often nonmonotonic, with abrupt changes in the direction of track movement. For example, a nonmonotonic track may have had a U-shaped pattern: observers would drive the stimulus value down with consistently correct responses and would abruptly begin making consistent errors at the end of the run (Saberi and Antonio, 2003). A related track pattern was a peak-type pattern: observers performed without errors at the beginning and end of a run and consistently made erroneous responses in the middle part of the track. These types of nonmonotonic patterns, however, were not observed for ILD adaptive tracks.

Outliers for observers with relatively low lag-click thresholds are not easily explained as resulting from the variance of a stationary threshold. Furthermore, in the ITD but not ILD conditions, observers often reported hearing a reversal of the cue to be detected; that is, the side to which they heard the lateralization cue was opposite to what would be predicted from the stimulus cue (as determined from the trial by trial feedback). Observers did not report reversals nor were the tracks nonmonotonic when the ICI was increased to 10 ms. We attribute outlier ITD thresholds to a potentially confusing secondary cue that is exclusive to the ITD but not the ILD condition. In the following section, we present a model that explains why threshold outliers and possible cue reversals occur for ITD but not ILD conditions. The model also explains why there is no effect of overall stimulus intensity on lag-click ILD conditions in contrast to the ITD condition.

4.2. Cue reversal and secondary peaks in the cross-correlation function

A possible explanation for perceiving a reversed cue in the ITD but not ILD condition may be related to the pattern of cross-correlation activity generated by dual-impulse stimuli. Cross-correlation analysis of two-transient stimuli that incorporate peripheral auditory mechanisms, or those that emphasize stimulus features such as the interaural phase spectrum, have proven useful to analysis of the precedence effects (Lindemann, 1986a,b; Saberi and Perrott, 1995; Tollin and Henning, 1998, 1999; Hartung and Trahiotis, 2001; Zurek and Saberi, 2003).

Fig. 4 shows the output of a cross-correlation model for two types of stimuli. We have selected two ICIs, 1 and 10 ms, for this analysis to cover a case where a very strong precedence effect is usually reported (1 ms) and a case where the precedence effect is quite weak (10 ms). See Saberi and Perrott (1990), Zurek and Saberi (2003), Zurek (1980), Yost and Soderquist (1984) and Saberi and Antonio (2003). Although for the current analysis we selected these two typical values, simulations showed that a 2-ms ICI produced results similar to the 1-ms case for which nonstationary adaptive tracks are also observed (Saberi and Antonio, 2003).

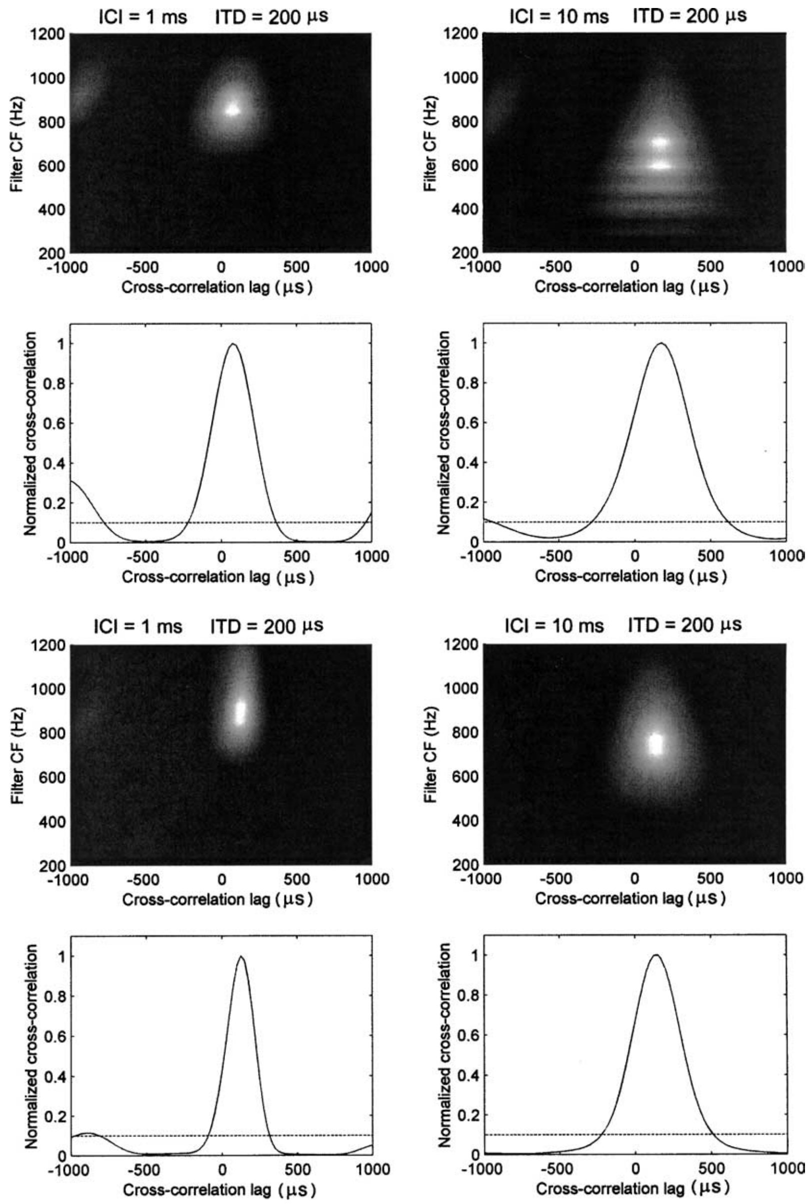

Fig. 4. Left and right panels show cross-correlation patterns for two-click stimuli with ICIs of 1 and 10 ms, respectively. The ITD was 200 μs. Row 1 shows the frequency-by-delay surfaces, and row 2 shows the cross-correlation functions integrated across frequency channels. Row 3 shows the effects of increasing the overall stimulus intensity on the cross-correlation patterns, and row 4 shows the cross-correlation functions integrated across frequency channels. All conditions in row 3 are the same as those for row 1, except that the GammaTone filter widths have been increased to simulate changes in auditory filter bandwidths with increasing intensity. Note the diminished secondary image and the sharper main peaks of the functions in row 4.

The model consisted of a GammaTone filterbank (Holdsworth et al., 1988) with 30 filters whose resonant frequencies were logarithmically spaced from approximately 100 to 1300 Hz. The stimuli were the two-click waveforms recorded at a sampling rate of 40 kHz at the output of the headphones as described in Section 2.1. These stimuli were filtered through the filterbank, followed by vth-law half wave rectification (Shear, 1987; $z(t) = x(t)^3$ for positive amplitudes, and zero otherwise), and cross correlation of the outputs of corresponding left- and right-channel filters. The resultant cross-correlation surface was frequency weighted using the function described by Stern et al. (1988) to emphasize the dominant frequency region in lateralization, and center weighted with a Gaussian envelope with a 1-ms σ to emphasize the greater weight given to delays near zero (Shackleton et al., 1992). The particular values or forms selected for these functions are not critical and do not affect the overall outcome. Finally, we weighted the model output with an exponential decay function $w(t) = e^{-t/k}$ with a time constant of $k = 6$ ms (Cherry, 1961) to emphasize more recent cross-correlation activity. This function is important in explaining the generally observed effects of ICI on the precedence effect.

Left panels of Fig. 4 show the model output for a two-click train with an ICI of 1 ms. The right panels are the same as the left panels, except that the ICI is 10 ms. The lead click is diotic and the lag click has an ITD of 200 μs. The model output activity is always shown at $t = 1$ ms after the peak of the lag click. The top row of panels shows the frequency-by-delay surfaces, and the second row shows the cross-correlation activities integrated across frequency channels (Shackleton et al., 1992). We will explain rows 3 and 4 at a later point.

Row 1, left panel shows a concentration of spectral energy near 800–1000 Hz. This is a result of a combination of factors, including the ICI (1 ms) and the frequency weighting function. We should note that although stimulus energy exists throughout the range of frequencies in this surface representation, it is attenuated relative to the peak near 800–1000 Hz and thus difficult to visually detect in this panel. Row 2, left panel shows two interesting features. First, the peak of the function occurs not at 200 μs (the lag-click ITD) but at approximately 75 μs, a value close to the average ITD of the lead and lag clicks. This shift is related to the temporal smearing of the lead and lag waveforms. These two waveforms fall well within the exponential decay window and, in addition, are passed through bandlimited low-frequency filters which have a long impulse response compared to an all-pass filter. Second, a minor peak is evident near a lag of −1000 μs. If we assume, as part of the model, a thresholding function or noise floor (dashed horizontal line) above which a detectable image is perceived, then the peak at −1000 μs may be considered as a possible source of the cue reversal reported by some observers in the ITD conditions.

Row 1, right panel of Fig. 4 shows the cross-correlation pattern for an ICI of 10 ms. Row 2, right panel shows this cross-correlation activity integrated across frequency. The peak of the function in this latter panel is near 175 μs, considerably closer to 200 μs. Clearly because all conditions are identical to those of the 1-ms ICI condition (left panels) except for the ICI, the more accurate positioning of the peak is a result of the ICI and a diminishing weight given to the lead click by the exponential decay function. The time constant of this function is 6 ms, i.e., after a 6-ms delay the weight (value of the exponential decay function) is 1/e or 0.37. At a 10-ms delay, this weight has dropped to 0.19, and therefore, the effect of the lead click at this ICI has decayed considerably, though not to zero.

A second observation is that the minor peak has been reduced in size, and therefore, a secondary image is less likely to lead to ambiguous cues (row 2, left versus right panel). The ripple observed in the top row, right panel is related to the 10-ms ICI, which produces a mild harmonic structure with a 100-Hz spacing. Unlike for the 1-ms ICI that generates energy near 1-kHz, for an ICI of 10 ms, spectral energy is more uniformly distributed. This effect, in conjunction with the effect of the frequency weighting function described above, result in a concentration of cross-correlation activity in the 600–800 Hz region.

4.3. Effects of stimulus intensity

The cross-correlation approach may also provide insight into the effect of stimulus intensity on thresholds, as seen in Fig. 1. This figure shows that increasing intensity reduces lag-click thresholds when the signal is an ITD, but not an ILD. It is well documented that auditory filter bandwidths increase with increasing stimulus intensity (Glasberg and Moore, 1990; Rosen and Baker, 1994; Rosen et al., 1998). It should be clear that increasing filter bandwidths would reduce secondary peaks that may be associated with secondary auditory images. These peaks are usually associated with the bandlimitted nature of filtered waveforms, as is often reported for the sidepeaks of bandlimitted ITD neural-tuning curves, the physiological equivalent of a cross-correlation function (Saberi et al., 2002). Rows 3 and 4 of Fig. 4 show the output of the cross-correlation model described above, with the only change being an increase in the bandwidths of the GammaTone filters. The exact increase in bandwidth is not important because our interest is in demonstrating the direction of change in peaks of the cross-correlation function after frequency convergence, but the increase was proportional to the original ERB of each filter, which increases with CF, and for reference it was 1.75 times the original bandwidths consistent with estimates reported by Rosen and Baker (1994) and Glasberg and Moore (1990) for a 30-dB increase in intensity.

As with rows 1 and 2, the left and right panels of rows 3 and 4 are for ICIs of 1 and 10 ms, respectively. There are two interesting effects to note in the left panel of row 4, compared to the left panel of row 2. First, the secondary peak on the side opposite to the stimulus ITD is smaller. Second, the skirts of the main peak have sharper slopes. Thus, an increase in stimulus intensity is predicted to reduce ambiguities associated with secondary images through a mechanisms that is exclusively related to ITD coding, but not ILD coding. It also predicts an increase in the signal-to-noise ratio for a signal interaural delay (sharper main peak), assuming a constant internal-noise variance (i.e., the noise that limits a position estimate). The first effect will affect lag-click ITD thresholds, particularly for the 1-ms condition, and the second effect will affect overall performance in all conditions, i.e., single and lag. The improvements in lag-click ITD threshold is of course evident as a reduction in the ratio of lag- to single-click thresholds (Fig. 1). There is also a predicted improvement in single-click ITD threshold with increased intensity. For the three intensities from low to high shown in Fig. 1, mean thresholds are 286, 275, and 247 μs; a small improvement of 16%. Although this effect is small, it is in the right direction and consistent with a sharpening of the main peak of the cross-correlation function with increased intensity.

Consistent with this analysis, Goverts et al. (2000) have shown that the precedence effect is most effective at mid-range stimulus levels (40–50 dB), declining at high intensities. A decline of the precedence effect was also reported when the stimulus intensity was held constant and background noise intensity was increased, a finding first reported by Chiang and Freyman (1998). Individuals with mild sensory neural hearing loss also show a decline in the strength of the precedence effect (Goverts et al., 2002). Possibly, the reduction of the strength of precedence at very low stimulus levels is based on a different process than its reduction at high levels. At low sensation levels, internal neural noise affects onset dominance in the same manner as increasing the level of background external noise. The cause of this weakening of the precedence effect when the signal level is close to the noise floor (internal or external) is not clear. Hafter and Buell (1990), however, have shown that binaural adaptation, a form of onset dominance in localization, is an active process from which the binaural system may be released if a sudden external temporal or spectral change is introduced during stimulus presentation. At high sensation levels, it is not likely that release from adaptation accounts for a decline in onset dominance and we consider increases in auditory filter bandwidths as the likely explanation.

4.4. Lag-click ILD discrimination

This explanation of the effects of intensity is consistent with the observation that intensity has little, if any, effect on ILD thresholds, at least for the range of intensities tested in our study. An ILD cue is encoded not within the putative cross-correlation structure, i.e., the medial superior olivary complex, but rather through a separate pathway, initially in the lateral superior olive (Caird and Klinke, 1983). These two cues only later converge at higher centers in the auditory tract. In models of lateral position estimation that employ a cross-correlation mechanism, the effect of an ILD is often included in a pathway parallel to the interaural timing pathway. The ILD pathway converges onto the output of the cross correlation mechanism as a multiplicative weighting function, that is, *after* the timing operations have been completed (Stern and Colburn, 1978). Because ILD weighting is a function of the ratio of amplitudes of the stimuli to the two ears, it is unaffected by increases in overall intensity. Furthermore, intensity-dependent increases in auditory filter widths are similar at the two ears, and thus, will leave the ILD weighting function, and consequently, ILD thresholds unchanged in such models. Naturally, at extreme levels when the overall intensity is quite low, substantially fewer neurons may entrain to the stimulus and ILD thresholds would be affected by the detection-limiting internal noise; however, even in this case, there is no reason to consider a differential effect on lag- versus single-click ILD thresholds.

It is, in addition, useful to note here that sensory memory decay will affect a lag-click ILD cue differently for 1- and 10-ms ICIs. For a 1-ms ICI, the composite waveform contains substantial energy from the lead click (which is equal-amplitude at two ears), and therefore, an ILD imposed on the lag click will represent a proportionately smaller overall level difference in decibels compared to the same ILD imposed on a single click. At an ICI of 10 ms, for which the influence of the lead click has decayed, an ILD in the lag click is more similar to that in a single click.

4.5. Concluding remarks

The current model predicts several observations in our data set, including changes in ITD lag-click threshold with increasing intensity, no effect of intensity on ILD-based precedence, as well as unstable adaptive tracks and subjective reports of double images. Other models of precedence have also been proposed to explain aspects of onset dominance. One class of such models incorporates neurophysiologically motivated stages that may include peripheral filtering, nonlinearities, temporal decay, inhibitory effects, and neural coincidence-detection as mathematically represented by cross-correlation analysis (Lindemann, 1986a,b; Zurek and Saberi, 2003). Another class takes a detection-theoretic approach, analyzing effects of echo inhibition from the standpoint of information transmission and loss of efficiency in signal processing (Saberi and Petrosyan, 2004) or a weighted decision process (Shinn-Cunningham et al., 1993). A third class of models emphasizes stimulus features. Among these are models proposed by Gaskell (1983), Tollin (1998), and Hartung and Trahiotis (2001).

A consideration of the latter class of purely stimulus-based models is useful at this stage as they have features common with our model. We describe, here, the Gaskell (1983) model since both the Tollin (1998) and Hartung and Trahiotis (2001) models are derivatives of the Gaskell model and are in many respects similar. Gaskell (1983) has provided analysis for the type of stimuli used in our ILD experiments. Using rectangular pulses, short ICIs (0.2–0.8 ms) and an ILD of 6 dB, Gaskell calculates two measures. The first, called a relative energy density (R.E.D.) is the frequency-dependent ratio of the stimulus levels to the two ears (in dB), and the second is the frequency-dependent interaural phase of the composite stimulus. At certain frequency bands, these two measures favor opposite spatial directions, and at other frequency bands both measures favor the same spatial direction. Gaskell has applied similar analysis to ITD-based precedence stimuli, and suggests that precedence may be based on anomalous localization when listening to frequency bands with contradictory cues.

Stimulus-based models, however, cannot readily generalize to a wider class of precedence phenomena without inclusion of an explicit neural inhibitory mechanism and high-level processing, e.g., precedence along the vertical plane (Blauert, 1971, 1997) or a number of onset-dominance effects that require long time-constants in the order of several seconds (Clifton, 1987; Saberi and Perrott, 1995). It is, in addition, unclear how stimulus-based models are affected by peripheral auditory mechanisms known to affect the spectro-temporal properties of the input stimulus. The Gaskell (1983) and Tollin (1998) models do not incorporate bandpass filter-banks or neural temporal decay (e.g., exponential decay mechanism) which are critical to processing of brief-duration stimuli. The Hartung and Trahiotis (2001) model, as well, does not account for rapid sensory decay or frequency-dependent dominance in localization. Our analysis suggests that binaural spectral dominance, a standard component of cross-correlation models (Stern et al., 1988; Stern and Trahiotis, 1997; Shackleton et al., 1992; Colburn, 1995; Saberi et al., 2002; Zurek and Saberi, 2003) would adversely affect the latter model's prediction of position estimates (see Fig. 5 of Hartung and Trahiotis, 2001).

Our approach is generally consistent with that described by Zurek and Saberi (2003) which considers precedence to be a neurally based weak inhibitory effect consistent with physiological reports (Cranford and Oberholtzer, 1976; Yin, 1994; Mickey and Middlebrooks, 2001), enhanced by ambiguities in the neural representation of the peripherally processed signal, and influenced by a central decision mechanism whose output determines the final percept. Where there is less ambiguity, as reported in studies of frozen-noise stimuli (Zurek and Saberi, 2003), or for higher stimulus levels, or relatively longer ICI, the lead impulse may have a diminished influence. A central processor that evaluates a number of pieces of evidence, in conjunction with a weak onset-inhibitory effect, would then generate a final position percept.

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