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4aPPb28. Effects of the stimulus spectrum on temporal weighting of binaural differences

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The influence, or "perceptual weight" of binaural information typically varies over the duration of a brief sound, as characterized by the temporal weighting function (TWF). Here, TWFs were measured for binaural lateralization of Gabor click trains (GCT) varying in carrier frequency from 1 to 8 kHz, and of broadband noise-burst trains (NBT) with repeated ("frozen") or newly-sampled ("fresh") noise across bursts. Interclick intervals (ICI) ranged 2-10 ms. On each of many trials, listeners judged the lateral position of a singly presented GCT or NBT. Lateral positions varied with the overall interaural time (ITD, ranging +/- 500 µs) and level (ILD, ranging +/-5 dB) differences applied to each stimulus. Additional random variation in ITD (+/- 100 µs) and ILD (+/- 2dB) was applied independently to each click within a train. TWFs were calculated by multiple linear regression of normalized position judgments onto the individual click ITD and ILD values, and indicated large ICI-dependent weights on the initial click, elevated weights near offset, and lower weights for interior clicks. Flatter TWFs were observed for "fresh" NBT stimuli than for GCT or "frozen" NBT stimuli. Results corroborate previous reports of temporal asymmetries in binaural processing of periodic stimuli across frequency. [Supported by R01 DC011548]

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INTRODUCTION

Sensitivity to interaural time differences (ITD) and interaural level differences (ILD) underlies our ability to localize sound sources in azimuth and to segregate competing sound sources in a wide range of situations. With real sound sources in real rooms, these cues vary over time as a consequence of distortion by echoes, reverberation, and competing sounds. To some extent at least, human and animal hearing seems to follow the statistics of those fluctuations, for example by strongly weighting binaural cues carried by early- versus late-arriving sound, consistent with the importance of localizing direct rather than reflected sound (Litovsky et al., 1999). This onset dominance holds in many (but not all) situations, and has been described variously in terms of binaural adaptation (Hafer and Dye, 1983), localization dominance (Freyman et al., 1997; Litovsky et al., 1999; Stecker and Hafer, 2002), and variation in binaural sensitivity over the duration of a sound (Zurek, 1980; Akeroyd and Bernstein, 2001; Stecker and Brown, 2010; Brown and Stecker, 2010).

Temporal weighting functions (TWFs) can be used to quantify onset dominance and related effects. TWFs plot the dependence of listeners' spatial judgments on the cues carried by each part of a sound, and can be estimated using statistical regression techniques. For example, Saberi (1996) and Brown and Stecker (2010) measured TWFs for ITD and/or ILD discrimination in trains of high-frequency filtered clicks, and observed large onset weights only when interclick intervals (ICI) were shorter than about 5 ms. Stecker and Hafer (2002, 2009) measured TWFs for the localization of filtered click trains in the free field. Again, strong onset dominance was observed for ICI less than 5 ms; in some conditions Stecker and Hafer (2002, 2009) also observed large weights for late-arriving sound (upweighting). Here, we extend the approach to measure TWFs for ITD- or ILD-based lateralization of trains of filtered impulses or broadband noise bursts. The goal is to determine whether either effect (onset dominance or upweighting) varies with cue type, stimulus spectrum, or periodicity.

EXPERIMENT 1: EFFECTS OF CENTER FREQUENCY ON TWF FOR FILTERED IMPULSE TRAINS

A potential explanation of ICI-dependent onset dominance in high frequency sounds follows from listeners' poor sensitivity to ongoing envelope ITD for ICI < 5 ms (Bernstein and Trahiotis, 2002). As a consequence, it is expected that listeners place more weight on the remaining intact cues—ILD (Stecker, 2010) and onset ITD (Hafer and Dye, 1983)—as the ICI falls below 5 ms. That is, onset dominance in ITD processing could simply reflect the loss of ongoing ITD information at high frequencies. If so, TWFs measured for sounds with significant low-frequency energy should not reveal ICI-dependent onset dominance, as no such rate limitation exists for ITD processing at low frequencies (Bernstein and Trahiotis, 2002). Experiment 1 of the current study tests this hypothesis by measuring TWF as a function of spectral frequency.

Methods

Subjects

Seven normal-hearing adult listeners participated in the experiment. Three were research assistants employed in the lab. The remainder were paid subjects naive to the purpose of the experiment. All subjects reported normal hearing and demonstrated pure-tone detection thresholds < 15 dB HL over the range 250-8000 Hz.
Stimuli

Stimuli were trains of 16 Gabor clicks (Gaussian-filtered impulses). Each click consisted of a carrier-frequency cosine multiplied by a Gaussian temporal envelope with $\sigma = 221 \mu s$. Carrier frequency was 1, 2, 4, or 8 kHz, depending on condition, and the half-maximal bandwidth approximately 1.8 kHz. Thus, the 1 kHz condition included significant low-frequency energy. Click trains were presented with peak-to-peak interclick interval (ICI) equal to 2, 5, or 10 ms, so that the total duration of each train was 32, 77, or 152 ms. Sounds were computed in MATLAB (Mathworks, Natick MA), synthesized at 48.828 kHz (Tucker-Davis Technologies RX6, Alachua FL), and presented via headphones (Sennheiser HD 485, Hannover Germany) at 70 dB peak-equivalent SPL (approximately 65–80 dBA, depending on condition).

ITD and ILD were tested in separate conditions, and applied to the stimuli as follows: on each trial in the ITD condition, a “base” ITD value was selected from the set {-500, -300, -100, +100, +300, +500 $\mu s$}. ITD of individual clicks within the train deviated from the base ITD by independent and uniformly distributed random values in the range $\pm 100 \mu s$. The ILD condition was treated similarly, with base ILD values of {-5, -3, -1, +1, +3, +5 dB} and per-click deviations spanning $\pm 2$ dB.

Procedure

Testing took place in a double-walled sound-attenuating booth (IAC, Bronx NY), with subject seated in a swivel chair and facing an 80-cm (diagonal) touch-sensitive display (elo Touchsystems 3200L, Tyco Electronics, Bermuda) at a distance of 50 cm. Head position was monitored continuously (Polhemus Fastrak, Colchester VT) to ensure stable head position during stimulus presentations.

On each trial, a single stimulus was presented, and listeners indicated the perceived lateral position of the stimulus by touching along a 55-cm horizontal bar displayed on the touch screen. Listeners were instructed to make an immediate eye movement to the judged position on the bar, and to maintain gaze while touching the foveated location with a finger. This instruction was intended to encourage listeners to rapidly orient to the sound’s location and not perseverate on then scaling judgment.

Listeners completed 90 trials per run (15 trials per base ITD or ILD value), and 4–8 runs per tested condition (combination of cue type and ICI).

Analysis

Response data were transformed to ranks (i.e. ranked according to lateral position) within each run, in order to minimize response nonlinearities and distributional differences across runs and subjects. Perceptual weights for each of the 16 clicks in a train were then estimated by multiple linear regression of the rank-transformed response $\theta_R$ onto the binaural cues applied to individual clicks $\theta_i$, using MATLAB:

$$\hat{\theta}_R = \sum_{i=1}^{16} \beta_i \theta_i + k.$$  

(1)

For comparison across subjects and conditions, regression coefficients $\beta_i$ were then normalized so that absolute values sum to 1 over the 16-click stimulus duration.

$$w_i = \frac{\beta_i}{\sum_{j=1}^{16} |\beta_j|}.$$  

(2)

The normalized weights $w_i$ comprise the TWF, and indicate each click’s relative influence on a listener’s judgments, and generally vary from 0 (no influence) to 1 (a perfect linear
relationship). Strongly negative values would indicate a biasing of judgments away from the click location. TWFs were estimated separately for each combination of listener, ICI, and cue condition (ITD or ILD), but combined data across all runs for that combination. 95% confidence intervals on $w_i$ were computed by normalizing the upper and lower confidence limits on $\beta_i$ by the denominator of Equation 2.

**Results and Discussion**

Group-average TWFs, computed by taking the mean across subjects for each click weight, are plotted in Figs. 1 and 2. Within each figure, separate panels plot TWFs for each combination of frequency (left to right) and ICI (top to bottom).

**FIGURE 1:** Temporal weighting functions for ITD-based lateralization. In each panel, normalized weights $w_i$ (y-axis) are plotted for each click in a train, as a function of the temporal order of the clicks (x-axis). Symbols plot the mean of normalized weights across subjects; error bars indicate means of 95% confidence intervals across subjects (a conservative interval for the mean weight). The dashed horizontal line in each panel indicates the value that would obtain if all clicks were equally weighted ($1/16$), while the solid line indicates zero. From left to right, panels plot TWFs for carrier frequency of 1, 2, 4, and 8 kHz. From top to bottom, panels plot TWFs for 2, 5, and 10 ms ICI.

**FIGURE 2:** Temporal weighting functions for ILD-based lateralization. Formatting as in Fig. 1

TWFs for ITD-based lateralization (Fig. 1) reveal several important features. First, weights...
on click 1 were significantly elevated at 2 ms ICI for frequencies of 1, 2, and 4 kHz, and moderately elevated for 8 kHz stimuli. This onset dominance was ICI dependent at all frequencies, failing to appear at 5–10 ms ICI in any case except for the 2 kHz center frequency, where it was significantly attenuated relative to 2 ms ICI. With respect to the hypothesis under test, we note that Bernstein and Trahiotis (2002) reported increasingly poor sensitivity to ongoing ITD as carrier frequency increased from 4 to 10 kHz. Here, we observed a reduction in onset dominance from 2 to 8 kHz, opposite to the prediction that onset dominance should increase as ongoing sensitivity is lost. The results may be better explained by considering the effects of peripheral filtering (Tollin, 1998; Tollin and Henning, 1999): the longer impulse responses of lower-frequency auditory filters more greatly obscure the ongoing binaural cues, so that the onset more strongly dominates the overall ITD at low frequencies.

A second feature of the data is the presence of large offset weights in some conditions. Notably, both the 1 and 2 kHz conditions at 2 ms ICI revealed large weights on click 16 which did not follow a monotonically increasing trend as described for upweighting by Stecker and Hafter (2009). Significant elevation of the offset weight in isolation would not be consistent with the mechanism proposed in that study (leaky temporal integration), but would be consistent with the role of auditory peripheral filters which continue to signal the offset ITD during the tail of their impulse responses. In contrast, at 5–10 ms ICI, increased offset weights appeared more similar to those described by Stecker and Hafter (2009), at least for 1 and 2 kHz. No significant offset weighting was observed at higher frequencies (4 and 8 kHz).

TWFs for ILD-based lateralization (Fig. 2) exhibit broad similarities to those obtained for ITD. Namely, onset dominance was observed at 2 ms ICI, but not 5 ms ICI, regardless of frequency. Monotonically-increasing weights near sound offset (upweighting) were observed across a broader range of frequencies and ICI values than for ITD, including all ICI values at 2 kHz, and 5–10 ms ICI at 4 kHz (in contrast to ITD, which showed no evidence of upweighting at 4 kHz). That result is consistent with greater sensitivity to ongoing ILD than to ongoing ITD in these conditions. At 1 kHz, significant weights were observed on click 16 in isolation at 2 and 5 ms ICI, again consistent with a strong influence of “ringing” peripheral filters carrying the offset ILD.

**EXPERIMENT 2: TWF FOR TRAINS OF BROADBAND NOISE BURSTS**

Whereas Experiment 1 investigated the effect of frequency using narrowband sounds, Experiment 2 utilized broadband noise carriers to ascertain the effects of spectral bandwidth and stimulus regularity. The stimuli were adopted from Freyman et al. (1997), who asked listeners to lateralize trains of 1-ms broadband-noise bursts repeating at 2 ms ICI. When the ITD of the onset burst differed from the remaining bursts, listeners lateralized such stimuli in the direction of the onset when successive bursts had identical waveforms, but in the direction of later bursts when successive bursts were independent. Those results are consistent with onset dominance for periodic sounds (as described in the introduction), but dominance of ongoing cues for aperiodic sounds (cf. Tobias and Schubert, 1959). Subsequently, Freyman et al. (2010) extended those results to the lateralization of noise-burst trains in which noise samples were identical within pairs of successive bursts but independent across bursts. In that case, listeners’ judgments appeared consistent with the ITD of the first burst in each pair (i.e., the “local” onset). Experiment 2 measures TWFs for repeated and non-repeated noise-burst trains to investigate whether features of narrowband TWFs depend on stimulus periodicity, or, in contrast, if changes in the stimulus fine structure can “rescue” later parts of the sound from onset dominance.
Methods

Subjects

Eight normal-hearing adult listeners participated in the experiment. All were paid subjects naive to the purpose of the experiment. All subjects reported normal hearing and demonstrated pure-tone detection thresholds < 15 dB HL over the range 250-8000 Hz.

Stimuli

Stimuli were trains of 1-ms bursts of Gaussian white noise. Each train presented 16 bursts at an ICI\(^1\) of 2 or 5 ms. Sounds were synthesized in MATLAB and presented over headphones, as described for Experiment 1. Noise waveforms were either computed independently across bursts in a train (i.e. “fresh” samples were generated), or were repeated from burst to burst (“frozen”). Conditions varied in the number of frozen bursts repeated before a fresh sample was generated. In one extreme condition, identical samples were used for all 16 bursts (i.e. completely frozen bursts), and we designate that condition “16 repeats.” The other extreme consists of fresh bursts on each presentation (“1 repeat”). Intermediate conditions presented fresh bursts after 8, 4, or 2 repeats. TWFs plotted in Fig. 3 indicate fresh bursts (“local onsets”) with filled symbols; open symbols indicate repeats of the preceding fresh burst.

Procedure and Analysis

Aside from differences in the stimuli employed, the experimental paradigm, including task, testing sequence, and analytical procedures, was identical to that of Experiment 1.

Results and Discussion

Fig. 3 plots group-average TWFs for each condition tested in Experiment 2. As before, a number of important features are apparent: First, strong ICI-dependent onset dominance was observed for both cues, in the form of significantly elevated click-1 weights.

Second, onset dominance was clearly stronger for periodic stimuli (16-repeats condition) than for aperiodic stimuli (1-repeat condition), consistent with a greater influence of ongoing cues in noise (Freyman et al., 1997). The magnitude of onset dominance tended to decrease with fewer repeats of each noise sample (i.e., as the stimulus became less periodic).

Third, elevated offset weights were observed in most conditions, often in a monotonically increasing pattern consistent with upweighting (Stecker and Hafter, 2009). Significantly elevated weights on click 16 in isolation were observed in fewer conditions, and only at 2 ms ICI, again consistent with a role of “ringing” peripheral filters (Tollin and Henning, 1999).

Fourth, and finally, we observed mixed evidence for greater weight on cues carried by fresh noise samples (filled symbols). For ITD at 2 ms ICI, we observed “local” onset dominance in the form of significantly greater weights on the first than the second repeat of each sample (most evident in the 4- and 8-repeats conditions). Interestingly, in those conditions the last repeat of each sample also benefitted from the sample change, consistent with the strong overall offset weights observed generally for ITD at 2 ms ICI.

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\(^1\)ICI was defined, as in Experiment 1, to be the time between onsets of successive burst or clicks.
FIGURE 3: Temporal weighting functions for noise-burst trains. As in Fig. 1, each panel plots mean normalized weights $w_i$ (y-axis), as a function of the temporal order of the clicks (x-axis). Error bars indicate mean 95% confidence intervals. The dashed horizontal line in each panel indicates the value that would obtain if all clicks were equally weighted (1/16), while the solid line indicates zero. From top to bottom, panels plot TWFs for noise-burst trains with noise samples repeating across 16 (top), 8, 4, 2, or 1 (bottom) sequential bursts. The first repeat of each new noise sample is indicated by a filled symbol; subsequent repeats are indicated by open (gray) symbols. From left to right, columns of panels plot TWFs for ITD-based lateralization at 2 ms ICI, ILD-based lateralization at 2 ms ICI, ITD-based lateralization at 5 ms ICI, and ILD-based lateralization at 5 ms ICI.

SUMMARY AND GENERAL DISCUSSION

Onset effects. Across conditions, and consistent with many past studies of high-frequency sounds, strong onset dominance was observed in TWFs for both low and high frequencies in Experiment 1, and also for broadband stimuli in Experiment 2. The magnitude of onset dominance was minimally dependent on sound frequency, with reduced effects at 8 kHz relative to lower frequencies. Thus, onset dominance in these stimuli is not due to rate-limited binaural processing confined to high frequencies (Bernstein and Trahiotis, 2002). Instead, it seems the potency of the onset cue per se renders ongoing cues weak regardless of sound frequency. Studies which eliminate the onset or gating cue to examine ongoing-cue sensitivity thus create an artificial situation that lacks not only the onset cue, but also its normal effects on the normal processing of ongoing cues.

In general, the ICI-dependence of onset dominance was observed to be similar to past studies: stronger onset dominance was observed at 2 ms ICI as compared to 5 and 10 ms ICI. Onset dominance was somewhat weaker for ILD than for ITD, consistent with the pattern observed across several studies in our lab (Brown and Stecker, 2010; Stecker and Brown, 2010, 2012). Onset dominance was reduced for aperiodic noise-burst trains as compared to periodic stimuli, consistent with a greater influence of ongoing cues in aperiodic stimuli (Freyman et al., 1997; Brown and Stecker, 2011).
Offset effects. Significantly elevated weights were also observed near sound offset in many conditions. These presented in two types of patterns. First, weights that increased monotonically over the last several clicks in a train were observed most commonly at ICI values of 5–10 ms. That pattern and ICI-dependence are consistent with upweighting as described by Stecker and Hafter (2002, 2009), who suggested its origin in leaky temporal integration of binaural cues. Interestingly, at 4 kHz and above, upweighting was observed for ILD but not for ITD, suggesting that the observations of Stecker and Hafter (2002, 2009) may have been driven primarily by ILD in their free-field stimuli.

The second pattern featured large weight on the offset click (i.e., click 16) alone. This was observed most prominently at 2 ms ICI for low frequency and broadband stimuli—both conditions which featured low-frequency energy. That pattern has not been reported in previous TWF studies and is not consistent with the effects of binaural temporal integration. It may instead reflect the continued signaling of offset cues by the fading response of peripheral auditory filters.

Peripheral versus central mechanisms. The strong onset dominance and large offset weights observed at 2 ms ICI in conditions with containing low frequency energy both suggest a role of peripheral filtering (Tollin, 1998; Tollin and Henning, 1999): a filter's response to the onset click interferes with and obscures later clicks, while its decaying response to the offset click sustains the offset cue. Thus, many if not all, TWF features at low frequency and short ICI may reflect the consequences of overlapping excitation in low-frequency peripheral filters. Future modeling studies could address that possibility.

In contrast to the peripheral account for low frequency and short ICI, other features remain more consistent—in our view—with the contribution of central mechanisms. It is not clear, for example, how much the auditory periphery contributes to onset dominance at high frequencies (4–8 kHz), where the filter responses are much shorter in time. Upweighting, observed at longer ICI (5 and 10 ms) and higher frequency (up to 4 kHz at least), exhibits a form consistent with temporal integration over a longer time course (at least on the order of 40 ms), and most likely reflects the temporal window of binaural integration (Akeroyd and Bernstein, 2001).

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