Modeling temporal weighting of interaural time and level differences in high-rate click trains

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Temporal weighting functions (TWFs) in sound localization

Temporal weighting functions (TWFs, examples above) reveal domininance of onset over later-arriving ongong spatial cues [interaural time and level differences (ITD and ILD), freefield azimuth, and monaural spectral cues] in sound localization and discrimination tasks for certain high-rate (> 200 Hz) modulated stimuli. That result is consistent with reports on the precedence effect (Wallach, Newman, and Rosenzweig 1948), Franssen effect (Hartmann & Rakerd 1989), binaural adaptation (Hafter & Dye 1983), and more recent reports on rate-limited processing of envelope ITD by normal hearing listeners (Bernstein & Trahiotis 2002), collicular neurons (Griffin et al. 2005), and bilaterally implanted cochlear impliant (CI) users (van Hoesel & Clark 1997, van Hoesel 2008).

Candidate mechanisms for onset-dominance and rate limitation in the processing of ongoing envelope ITD have included post-onset inhibitory processes (Zurek 1980, Lindemann 1986, Houtgast & Aoki 1994), adaptation of binaural inputs (Hafter & Dye 1983), low-pass filtering of temporal envelope representations (Bernstein & Trahiotis 2002), relative weighting of spatial cues according to their plausibility (Rakerd & Hartmann 1985), interactions between successive stimuli within the auditory periphery (Tollin & Henning 1998, Hartung & Trahiotis 2001), and combinations of these effects (e.g., Zurek & Saberi 2003).

Upweighting of late-arriving sound. Several, but not all, studies of temporal weighting of auditory spatial cues have additionally demonstrated an importance of late-arriving sound (Zurek 1980, Akeroyd & Bernstein 2001, Stecker & Hafter 2002, 2009, Macpherson & Wagner 2008). Accounts of this finding have focused on memory mechanisms, e.g. binaural temporal integration (Akeryoyd & Bernstn 2001) and recency effects (Stecker & Hafter 2009).

Stimulus dependence of onset dominance. In contrast to high-rate narrowband stimuli, slower modulation rates or increased bandwidth can lead to greater dependence of sound localization on ongoing than onset cues. Freyman et al. (1997) ascribed this difference to the ambiguous nature of binaural cues in spectrally sparse (narrow bandwidth and/or temporally regular high-rate modulation) versus spectrally dense (wide bandwidth, irregular and/or slow modulation) stimuli.

Restarting and the effects of random interstimulus intervals. Hafter & Buell (1990) showed that brief disruptions of an ongoing stimulus enhance sensitivity to binaural information in a manner consistent with a transient release from binaural adaptation ("restarting"). That result suggests that onset dominance might be reduced or avoided by stimuli with irregular modulations that prevent the establishment of binaural adaptation through continuous restarting. Recently, Laback & Majdak (2008) exploited this possibility by randomizing the interpulse intervals (IPI) of high-rate pulse trains delivered to bilateral CI users. As hypothesized, they observed improved sensitivity to ITD carried by these "jittered" pulse trains compared to regular trains.

The goal of this study is to examine the effects of peripheral interaction, envelope low-pass filtering, post-onset inhibition, and binaural temporal integration on TWFs for (primarily high-rate narrowband) click-train stimuli. Stimuli vary in interclick interval (ICI) and incorporate putative restarting triggers (gaps, squeezes, and ICI jitter).

Effects of peripheral filtering

Actions of auditory peripheral filtering (above) were simulated in MATLAB using the Binaural toolbox (Akeroyd 2001) function `mgammatonefilterbank`. Stimuli were Gabor click trains with regular ICI (top section), irregular ICI (middle section, jittered at k=0.9 as per Laback & Majdak 2008), or Gabor click trains with restarting triggers (Buell & Hafter 1990) inserted between clicks 8 and 9 (lower section). Triggers consisted of momentarily lengthened ICI ("gap," upper plots) or shortened ICI ("squeeze," lower plots). In all cases, carrier frequency was set to 4000 Hz, and Gabor duration to 2ms (nominal, 3 dB BW ~900 Hz).

Left plot in each panel: Individual traces depict waveform (gray) and envelope (black line) of filter outputs for gammatone filters with CF equal to 500 (lower trace), 100, 2000, 4000, and 8000 Hz; top trace in each panel plots waveform and envelope of unfiltered click train. Filter outputs were normalized in amplitude to reveal temporal characteristics of responses away from carrier frequency. Envelopes were calculated by full-wave rectification followed by bidirectional low-pass filtering at 1000 Hz (3rd order Butterworth using `filtfilt` in MATLAB).

Center and right plots in each panel: modulation spectra, (amplitude of the 8192-point FFT of filter-output envelope). For rightmost plots, envelopes were subjected to 150 Hz lowpass filtering (2nd order Butterworth) as described by Bernstein & Trahiotis (2002). Note the low amplitude of modulation energy below 150 Hz in the case of regular short ICI, increased somewhat by introduction of jitter or restarting trigger.

Binaural cross-correlation

Binaural cross-correlograms (above) were computed using the Binaural toolbox (Akeroyd 2001) function `mcorrelogram` with transduction option `'envelope'` (half-wave rectification plus power-law [0.2 then 2.0]) and binaural cross-product output. Stimuli were Gabor click trains; above panels are arranged according to ICI, as described for peripheral filter outputs at left. Left panels present responses to broadband (nominal Gabor duration 0.1 ms) click trains; right panels present narrowband (Gabor duration 2 ms) click trains. In each case, a static ITD of 100 µs favors the left ear.

Note greater output for low-frequency channels when ICI is long (low modulation rate = low fundamental frequency of periodic modulation) compared to short ICI. Jittering ICI enhances activity in these low frequency channels.

TWFs from binaural model

Temporal weighting functions (above) were computed from the binaural cross-correlation model as follows: trains of 16 Gabor clicks (4000 Hz carrier freq) stimuli were generated with indivual click ITDs drawn from a uniform distribution spanning [-200 200] µs. The binaural cross-product computed by the model (Binaural toolbox function `mcorrelogram`) and the ITD channel with maximum activity (summed across frequency) was selected as the lateralization "response" for each stimulus (see **A** at left). This process was repeated 500 times per stimulus condition. As in psychophysical weighting studies, multiple linear regression of response ITD onto individual click ITD values was used to compute weights for each click in the train. Normalized weights (symbols) and 95% confidence intervals (vertical lines) are plotted in TWFs above. Dashed line indicates equal-weighting point.

Lefts (A) example of summed binaural cross-product for a single stimulus; **(C and D)** dependence of response ITD on click 1 and mean ITD, respectively, across trials in one condition (2.5 ms ICI); **(B)** resulting TWF demonstrates strong dependence of response on clicks 1 and 16, compared to intermediate clicks.

TWFs from post-onset weighting plus binaural temporal integration

Akeroyd & Bernstein (2001) used a combination of post-onset weighting (Houtgast & Aoki 1994) and a sliding window of binaural temporal integration (Bernstein et al. 2001) to account for variation in listener's sensitivity to ITD of brief noise bursts as a function of a burst's temporal placement within a longer diotic "fringe" (Zurek 1980). Stecker & Hafter (2009) implemented the model of Akeroyd & Bernstein (2001) to generate TWFs for Gabor click trains varying in duration, in order to assess the ability of that model to account for upweighting of late-arriving sound in freefield localization. Here, we adapt the model to generate TWFs for click trains varying in ICI (above). Parameters are identical to those used by Akeroyd & Bernstein (2001) to account for ITD discrimination in their data. Note that, unlike the binaural cross correlation model (Hartung & Trahiotis 2001), the post-onset weighting of Houtgast & Aoki (1994) correctly predicts onset dominance for ICI at and beyond 5 ms: Temporal integration imbues the model with memory that causes upweighting that extends beyond the offset click, but due to its constant *temporal* extent, the number of clicks affected by upweighting is significantly reduced for longer ICI. Adjusting the time constants of temporal integration can produce a more "sluggish" system with relatively more gradual (though temporally fixed) upweighting.

Quantifying predictions of onset dominance and upweighting

Average ratio (AR, Saberi 1996) characterizes the degree of onset dominance as a ratio of the onset (click 1) weight to mean of remaining weights. Stecker & Hafter (2009) modified Saberi's definition to better deal with TWFs exhibiting significant upweighting by replacing the denominator with the mean of weights excluding the onset or offset clicks.

Left top: AR of the onset click plotted against ICI for Gabor click trains with regular ICI. Solid lines plot predictions based on binaural cross-correlation (black curve) and the combined weighting model of Akeroyd & Bernstein (2001, blue curve). Blue asterisks plot predictions of binaural cross-correlation for jittered ICI (k=0.9), and red symbols for restarting with gap (+) and squeeze (x) conditions. Black symbols plot experimental data reported by Saberi (1996, square), Stecker & Hafter (2002, upward-pointing triangle), and Stecker & Hafter 2009, (downward triangle). Note that binaural cross-correlation appears to under-predict onset dominance, especially for ICI longer than 3-5 ms. Effects of jitter are confined to short ICI.

Left middle: AR of the offset click plotted against ICI. Format and symbols identical to upper plot. Note that predicted AR for offset is weaker overall than for onset, but is similarly affected by ICI (specifically, upweighting is not predicted for ICI>3.5 ms).

Left bottom: rise in weights from click 2 to click N-1 (click 15 in this case) was used by Stecker & Hafter (2009) to characterize gradual upweighting observed in freefield TWFs. Neither model predicts gradual increases of the type observed; thus little dependence on ICI is present in the predictions.

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