Across-frequency processing of interaural time and level differences in perceived lateralization

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Summary
Interaural time and level differences (ITDs and ILDs) contribute to the localization of sound sources; however, reverberation or use of cochlear implants diminishes the role of ITDs. Intracranial lateralization was investigated in normal-hearing listeners using correlated or uncorrelated narrowband noises, where ITDs and/or ILDs from a typical headrelated transfer function were applied. Results showed that ITDs and ILDs contributed to lateralization for correlated noises. ILDs contributed to lateralization for uncorrelated noises. Frequency-dependent ITD and ILD weighting occurred. These data help understand the across-channel processing of ITDs and ILDs, particularly when ITDs may not be available to the listener.

Keywords
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1. Introduction
Complex sounds are localized in the horizontal plane by processing interaural time differences (ITDs) and interaural level differences (ILDs). In quiet conditions, listeners with normal acoustic hearing demonstrate a low-frequency (<1500 Hz) ITD dominance in localizing sound sources [1]. Also, ITDs generated by the head are relatively consistent across frequency, which is likely a powerful contributor to the localization of complex sound sources (sometimes called “straightness” [2]).

There are instances in which the role of ITDs in sound localization are diminished compared to ILDs. Highly reverberant environments smear ITD and decrease the interaural coherence of the signal [3, 4]. ITDs are also not conveyed well through bilateral cochlear implants (CIs), auditory prostheses that partially restore hearing and speech understanding to people with severe-to-profound hearing loss. Bilateral CI users demonstrate an ILD dominance in sound localization [5].

It is presently unclear how across-frequency ILD processing occurs even for acoustic sound sources under typical auditory processing because ITDs typically dominate the perception [1]. The purpose of this study was to investigate how acrosschannel ITD and ILD processing
affects the intracranial lateralization of complex sounds in normal-hearing listeners. We specifically want to determine if a frequency-specific weighting influences across-channel ILD processing.

Previous studies suggest ILD frequency dependence exists. First, frequency-dependent ILDs are physically produced by the head, where ILDs for sound sources off the midline tend to increase with increasing frequency because the wavelength of sound becomes comparable or smaller than the head, making it an effective obstruction [6, 7]. Second, neural processing of ILDs suggests possible frequency dependence. For tones or narrowband noises presented over headphones, ILD thresholds [8–10] and ILD lateralization [11, 12] demonstrate a small frequency dependence. Binaural interference paradigms (a diotic target and remote diotic interferer), a way to assess across-channel binaural processing, show a frequency dependence in ILD thresholds and lateralization [10].

To investigate across-channel ITD and ILD processing, we presented narrowband noises to normal hearing listeners over headphones where the ITDs and ILDs were derived from head-related transfer functions (HRTFs). Novel to this study is that we varied the interaural cross-correlation of the bands of noise to alter the usability of ITDs to perform the lateralization task. We hypothesized that ITDs and ILDs contribute to lateralization at any frequency, but low-frequency ITDs are more heavily weighted when the noise bands began as interaurally correlated. In contrast, ILDs are more heavily weighted when the noise bands began as interaurally uncorrelated. In addition, we hypothesized that ILDs at higher frequencies are more heavily weighted than lower frequency channels because large and informative ILDs naturally occur at high frequencies.

2. Method

2.1. Listeners

Seven normal-hearing listeners were tested in this study (ages 19–44 yrs, average = 28.2 yrs, two were the authors). They had hearing thresholds <20 dB hearing level at octave frequencies between 250 and 8000 Hz, and interaural asymmetries were <10 dB.

2.2. Stimuli

The stimuli consisted of narrowband noises at different center frequencies (CFs). The noises had a 300-ms duration and were temporally shaped by a Tukey window with a 100-ms rise-fall time. They began and ended synchronously. The CFs of the bands were 501, 1001, 1938, 2876, and 5001 Hz, which were derived from five electrode bandpass filters used in a common CI frequency-to-electrode allocation. The CFs were derived from a CI because bilateral CI users primarily utilize ILDs to localize sounds [5]. The bandwidth (BW) of the narrowband noises was one equivalent rectangular bandwidth according to [13]. The normalized interaural cross-correlation (ρ) of each band was set to one (correlated) or zero (uncorrelated).

ITDs and ILDs were extracted from an HRTF database [14] using in-the-ear microphones, therefore using interaural differences produced by the head, torso, and pinna. The interaural differences corresponded to angles of 0°, ±15°, ±30°, ±45°, ±60°, ±75°, and ±90°.
Single- and multi-band conditions were presented to the listeners. There were five single-band conditions corresponding to the five CFs that were analyzed in the HRTF. There were two three-band conditions, one with a wide spacing (CFs=501, 1938, and 5001 Hz) and one with a narrow spacing (CFs=1001, 1938, 2876 Hz). There was one fiveband condition. Three different sets of interaural differences were applied to the bands: (1) HRTF-derived ITDs and ILDs (called ITD+ILD), (2) HRTF-derived ITDs with all ILDs set to zero (called ITD only), and (3) HRTF-derived ILDs with all ITDs set to zero (called ILD only). A subset of conditions consisting of the uncorrelated band conditions for the ILDs had the values reversed across frequency channels (i.e., low-frequency channels had the ILDs from the high-frequency channels and vice versa) to evaluate the possible frequency dependence of ILD processing.

2.3. Procedure

Listeners performed an intracranial lateralization task where they marked the perceived location of a sound source on a graphical representation of the head on a personal computer [10]. They initiated each trial with a button press. The sound was generated in MATLAB, then delivered to a real-time processor and digital-to-analog converter (Tucker-Davis Technologies RP2.1), a headphone buffer (HB7), and finally a pair of circumaural headphones (Sennheiser HD650s). Listeners were in a double walled sound attenuating booth (IAC).

The conditions were randomized in a method of constant stimuli. Five trials per condition were presented and responses for negative angles were mirrored and combined with positive angles for data analysis. For 0° where there was no mirroring, 10 trials were presented. Also, any conditions that were repeated were not remeasured (e.g., 0° was the same condition for all three interaural difference sets).

3. Results and Discussion

Figure 1 shows the results of the study. For the correlated single-channel noise bands (first row), lateralization mostly increased with increasing angle for the ITD+ILD (panel A), ITD-only (panel B), and ILD-only (panel C) conditions. The reversals of the lateralization at midfrequencies and large angles in the ILD-only condition was a result of the acoustical bright spot [15]. The ITD+ILD conditions had larger lateralization than the ITD-only and ILD-only conditions. This likely occurred because the other interaural cue was set to a value of zero in the ITD-only and ILD-only conditions, which is consistent with the hypothesis that ITDs and ILDs contribute to lateralization at all frequencies. The lateralization decreased with increasing frequency for ITD-only conditions (panel B), likely because of the transition from usable and potent low-frequency fine-structure to envelope ITDs [1]. In addition, lateralization increased with increasing frequency for ILD-only conditions (C) because the ILDs that were used are naturally larger at higher frequencies [6, 7]. For the multi-band conditions (panels D-F), the ITD+ILD condition produced the largest lateralization, similar to the single-band conditions; interestingly, the ITD+ILD conditions produced the most consistent lateralization across the multi-band conditions, likely because of the consistent ITDs [2] and realistic ILDs that were applied. Small differences across the three multi-band
ITD-only (panel E) and three ILD-only (panel F) conditions suggest a small frequency dependence of across-channel ITD and/or ILD processing.

For the uncorrelated single-channel conditions (second row), the ITD+ILD conditions (panel G) were equivalent to the ILD-only conditions (I). In addition, the ITD-only conditions (H) produced no lateralization [3]. Therefore, using uncorrelated noise bands effectively removed the contribution of ITDs to the lateralization percept, and thus provides a more realistic simulation for a majority of cochlear-implant users than using stimuli with usable ITDs [5]. For the multi-band conditions, the ITD+ILD conditions (J) were equivalent to the ILD conditions (L). Again, the ITD conditions produced no lateralization (K). Small differences across the three multi-band ITD+ILD (J) and three ILD-only (L) conditions again suggest a small frequency dependence of across-channel ITD and/or ILD processing. Comparing the lateralization for the correlated and uncorrelated ILD-only conditions, lateralization was larger for the uncorrelated conditions, likely because there was no consistent zero ITD that pulled the auditory image to the midline.

To assess if ILDs demonstrate frequency dependence, reversed ILDs were applied to the uncorrelated bands [i.e., the ILDs from the high-frequency bands (e.g., 5001 Hz) were applied to the low-frequency bands (e.g., 501 Hz) and vice versa]. The results are shown in Fig. 2. The reversed ILD conditions produced similar patterns of lateralization, but there were differences in the single-channel extents of lateralization (panel E), where ILDs applied to the 5001-Hz band produced larger lateralization than when the same ILDs were applied to the 501-Hz band (two-way repeated-measures ANOVA with factors azimuth and band; main effect of band, F(4,24)=12.3, p<0.0001, \(\eta_p^2 = 0.67\))

4. Summary and Future Directions

This study showed that both ITDs and ILDs contribute to the across-channel processing of intracranial lateralization, and that there is a frequency dependence [larger lateralization at low frequencies for ITDs, at high frequencies for ILDs (Figs. 1–2)]. Future directions include modeling frequency-dependent weighting of single-channel ITD and ILD lateralization for the multi-channel conditions. The data suggest the multi-channel ITD-only lateralization might be best modeled by using the single band with the largest extent of lateralization, irrespective of the frequency of the band (Fig. 1B, E). In addition, the multi-channel ILD-only lateralization might be best modeled by averaging the single-band lateralization across bands, as suggested by the decrease in lateralization as azimuth increases to 90° for the standard and reversed ILD conditions (Fig. 2B, D).

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Fig. 1.
Lateralization data for correlated bands (top row) and uncorrelated bands ($\rho = 1$; bottom row). The left three columns show the single-band conditions; the right three columns show the multi-band conditions and the frequencies (in kHz) included in the three-band conditions are in the legend. Data points represent averages and error bars are ±1 standard error in length.
Lateralization for uncorrelated noise bands. The colors and symbols follow the same conventions as Fig. 1. Standard ILDs are applied to the stimuli used in the first row (data from Fig. 1I, 1L are plotted again); reversed ILDs are applied to the stimuli used in the second row; the third row shows the difference in lateralization based on conditions that had the same ILD applied (the ILDs were matched across frequency bands).