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The effect of interleaved filters on normal hearing listeners' perception of binaural cues

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Abstract

Objectives—Hearing impaired individuals often have difficulty in noisy environments. Interleaved filters, where signals from neighboring frequency regions are sent to opposite ears, may benefit those individuals but may also reduce the benefits of spatial cues. This study investigated the effect of interleaved filters on the use of spatial cues.

Design—Normal hearing subjects' sound localization abilities were tested with and without interleaved filters.

Results—Participants' localization performance was worse with interleaved filters but better than chance. Interleaving in high-frequency regions primarily affected interaural level difference cues and interleaving in low-frequency regions primarily affected interaural time difference cues.

Conclusions—Interleaved filters reduced but did not eliminate the benefits of spatial cues. The impact was dependent on the frequency region they were used in, indicating that it may be possible to use interleaved filters in a subset of frequency regions to selectively preserve different binaural cues.

Introduction

Sending signals from neighboring frequency regions to opposite ears (interleaving) helps listeners with sensorineural hearing loss, HA users, and some CI users perform better in noisy environments (Kulkarni et al. 2012; Lunner et al. 1993; Tyler et al. 2010; Zhou et al. 2012). However, interleaving potentially adversely affects both interaural time difference (ITD) and interaural level difference (ILD) cues because both rely, to varying degrees, on overlapping areas of excitation across ears (Francart et al. 2007; Poon et al. 2009). The degradation of binaural cues may be reduced by presenting some frequency regions to both ears and interleaving others across ears (Takagi et al. 2010). The goal of this study was to determine how interleaving, and the frequency region chosen for interleaving, affects localization.

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Materials and Methods

Subjects

Participants were eleven normal-hearing (NH) subjects (average age: 35.8 years). All had symmetrical hearing and pure-tone thresholds ≤ 25 dB HL from 250 to 8000 Hz.

Stimuli

Participants were tested with the Source Azimuth Localization Test (SALT; Aronoff et al. 2012; Chan et al. 2008), a test consisting of a broadband impulsive sound at one of twelve virtual locations. The stimulus was processed with head-related transfer functions (HRTFs) from Chan et al. (2008), simulating sources behind the head, spaced 15° apart. For details see Aronoff et al. (2012). Versions of the HRTFs were created preserving different cues. ITD-based HRTFs preserved the original phase response, with the magnitude response replaced by that from the right ear for 180° . ILD-based HRTFs preserved the original magnitude response, with the phase response replaced by that from the right ear for 180° .

An eight-channel filter bank was applied to the HRTF-processed signal. The lowest and highest bands were lowpass (cut-off freq. = 300 Hz) and highpass filters (cut-off freq. = 4500 Hz), respectively. Cutoff frequencies were determined 3 dB below the passband value. The remaining filters were bandpass filters equally spaced on a logarithmic scale (center frequencies for Bands 2–7 were 386, 605, 951, 1594, 2345, and 3683 Hz). Each band was implemented using a 1024 tap FIR filter having linear phase characteristics, with a sampling frequency of 24 kHz. All filters had 0 dB gain in the passband to prevent coloration.

Four configurations were used (see Figure 1):

1. **Bilaterally Matched.** Outputs from all bands were presented to both ears.
2. **Fully Interleaved.** Outputs of odd bands were presented to one ear, and even bands to the other.
3. **High Interleaved.** Outputs of the lowest two bands were presented to both ears and the other bands were interleaved across the ears.
4. **Low Interleaved.** Outputs of the highest two bands were presented to both ears and the other bands were interleaved across the ears.

Procedures

The experiment was conducted under headphones (Sennheiser HDA 200) in a single-walled sound booth. Stimuli were presented via an Edirol UA-1X with a HeadRoom AirHead headphone amplifier. The task was to identify the stimulus location. For details see Aronoff et al. (2012).

All filter configurations were used with the ITD+ILD HRTF. The High Interleaved and Low Interleaved configurations were also used with the ITD- and ILD-based HRTFs. To minimize floor effects, the ITD- and ILD-based conditions were only used with the eight participants whose Bilaterally Matched ITD+ILD-based root mean square (RMS) error was 24 degrees (average NH performance in Aronoff et al., 2012). The testing order was

randomized. The procedures were approved by the St. Vincent Medical Center institutional review board.

Robust statistical techniques were adopted to minimize the potential effects of outliers and non-normality (see the Appendix in Aronoff et al. 2011). These included bootstrap analyses, which avoid assumptions of normality by using distributions based on the original data rather than an assumed normal distributions and trimmed means, a cross between means and medians.

Results

ITD+ILD-based HRTF

A percentile-*t* bootstrap repeated-measures ANOVA with 20 % trimmed means indicated that localization was significantly affected by filter configuration ($F_{crit} = 3.07$, $F_t = 3.13$, where $F_t > F_{crit}$ indicates significant results for $\alpha = 0.05$; see Figure 1). Post-hoc analyses were conducted using percentile bootstrap pairwise comparisons with 20% trimmed means and familywise error controlled using Rom's correction (Rom, 1990). The Fully Interleaved and High Interleaved configurations were significantly worse than the Bilaterally Matched configuration ($p < 0.01$; shown with asterisks in Figure 1). There were no other significant differences between configurations ($p > .05$ for all other comparisons). Localization was better than chance (48.4° ; see Aronoff et al., 2010) for all configurations, suggesting that interleaving reduced rather than eliminated the benefit of spatial cues.

ITD- and ILD-based HRTFs

To determine if ITD- and ILD-based localization differed as a function of the High and Low Interleaved configurations, a percentile bootstrap two-way repeated-measures ANOVA with 20% trimmed means was conducted. There was a significant main effect of configuration ($p < .0001$), no significant main effect of HRTF type ($p = .8$), but a significant interaction between configuration and HRTF type ($p < .0001$). Two sample percentile bootstrap pairwise comparisons with 20% trimmed means were conducted. ITD cues were significantly more detrimentally affected by interleaving in low frequency regions ($p < 0.01$) and ILD cues were significantly more detrimentally affected by interleaving in high frequency regions ($p < 0.05$; see Figure 2).

Discussion

This study examined the effect of interleaved filters on binaural cues. Localization performance was degraded, consistent with previous findings (Takagi et al. 2010; Tyler et al. 2010). However, some localization abilities were still preserved.

ITD-based performance was significantly worse when interleaving in low frequency regions, while ILD-based performance was significantly worse when interleaving in high frequency regions. The ability to selectively preserve ITDs or ILDs has implications for different populations. CI users gain little benefit from ITDs with clinical speech processors (Aronoff et al. 2010; Seeber et al. 2008), so interleaving in low frequency regions may preserve their

usable cues. HA users gain little benefit from ILDs (Kalluri et al. 2007), so interleaving in high frequency regions may preserve their usable cues.

Conclusions

Interleaved filters partially degraded NH localization abilities. The binaural cue affected depended on the interleaved frequency regions, suggesting it may be possible to selectively preserve different binaural cues.

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Figure 1. Schematic of the filter configurations. The filled in boxes represent the bands that were presented to the specified ear (top). RMS error (degrees) for each filter configurations (N=11). Bars indicate 20% trimmed means and error bars indicate winsorized SE. (bottom).

Figure 2. RMS error (degrees) for ITD- and ILD-based HRTFs conditions (N=8). Bars indicate 20% trimmed means and error bars indicate winsorized SE.