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Revisiting the detection of interaural time differences in listeners with hearing loss

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Abstract: Sensitivity to interaural time differences (ITDs) was measured in two groups of listeners, one with normal hearing and one with sensorineural hearing loss. ITD detection thresholds were measured for pure tones and for speech (a single word), in quiet and in the presence of noise. It was predicted that effects of hearing loss would be reduced for speech as compared to tones due to the redundancy of information across frequency. Thresholds were better overall, and the effects of hearing loss less pronounced, for speech than for tones. There was no evidence that effects of hearing loss were exacerbated in noise.

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1. Introduction

Interaural time differences (ITDs) are one of the primary cues available to the auditory system for determining the spatial location of sound sources. ITDs come about due to the separation of the two ears in space, and the resulting differences in path length that a sound must travel to reach the two ears. ITDs are carried in the fine structure of low-frequency sounds, as well as in the envelopes of high-frequency sounds. Human listeners with normal hearing (NH) are exquisitely sensitive to ITDs, with reported detection thresholds below 10 μs under optimal conditions (Stecker and Gallun, 2012; Thavam and Dietz, 2019).

Many previous studies have measured ITD sensitivity in listeners with sensorineural hearing impairment (HI) using pure tones or narrowband noises (e.g., Hawkins and Wightman, 1980; Buus *et al.*, 1984; Smoski and Trahiotis, 1986; Gabriel *et al.*, 1992; Lacher-Fougère and Demany, 2005; Spencer *et al.*, 2016). In general, there appears to be a detrimental effect of hearing loss, although variability is high and thresholds range from normal to unmeasurable. One possible explanation for the wide variety of results for narrowband stimuli is that listeners with hearing loss have scattered regions of neuronal loss in each ear, which lead to particular frequency regions in which there are not enough intact neurons on each side to support robust interaural comparisons. If this is the case, then increasing the bandwidth should provide redundant information across multiple frequency regions and reduce the influence of the damaged regions. Consistent with this idea, the one study we are aware of that measured ITD thresholds for broadband noise stimuli in NH and HI listeners found no difference between the groups (Häusler *et al.*, 1983). However, more comprehensive studies that include a direct comparison of narrowband and broadband stimuli are lacking. Moreover, we know of no studies that have examined ITD thresholds in HI listeners for more complex stimuli such as speech.

In this study we measured ITD sensitivity for pure tones at different frequencies and for speech, in quiet and in the presence of noise. The inclusion of noise, which effectively decorrelates the target, was done to address the possibility that effects of hearing loss might be better revealed under these conditions than in quiet (e.g., Henry and Heinz, 2012). All conditions were tested in two groups of relatively young, healthy listeners who differed primarily in their hearing status (NH or HI). These two groups enabled us to focus on the effects of hearing loss without the confounding effects of age that are present in almost all of the currently available data (see Moore, 2019). We tested the specific hypothesis that any differences in ITD sensitivity between the groups would be smaller for broadband stimuli than for narrowband stimuli.

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2. Methods

2.1 Participants

The participants in the study were 18 adults, nine with NH (ages 21–28 years, mean age 24), and nine with bilateral sensorineural hearing loss (ages 20–42 years, mean age 28). The HI listeners had losses that varied in severity, with a pure-tone average (PTA; mean threshold across both ears at 0.5, 1, and 2 kHz) ranging from 19 to 74 dB hearing level (HL) (mean 49 dB HL).[1] All losses were relatively symmetric (difference in PTA between the ears of less than 10 dB). PTAs ranged from −3 to 8 dB HL in the NH group (mean 2 dB HL). Age and PTA were not significantly correlated across listeners ($r = 0.39$, $p = 0.1$). Participants were paid for their participation and gave informed consent. All procedures were approved by the Boston University Institutional Review Board.

2.2 Stimuli

Pure tone stimuli had frequencies of 350, 750, or 1150 Hz and were 500 ms long including 10-ms on and off ramps. The speech stimulus was a single utterance of the word "two" spoken by a female talker (459 ms long). This word has been used in previous studies (e.g., Best *et al.*, 2011) and was used here to facilitate comparisons. The 750 Hz tone and the speech stimulus were also tested in noise. When a noise masker was present, it was a Gaussian noise matched in duration to the tone or speech target stimulus, and had 10-ms on and off ramps. Speech and noise stimuli were low-pass filtered at 1500 Hz using a third order Butterworth filter. The reason for confining all signals to the region below 1500 Hz was to focus our investigation on fine-structure rather than envelope ITDs.

On each trial, the target stimulus was presented in four intervals, separated by 200 ms of silence. In either the second or third interval, the target was given a left-leading ITD. The remaining three intervals all served as reference intervals in which the target was diotic. ITDs were imposed via a phase shift in the frequency domain, which allowed for ITDs smaller than the sampling period. Noise maskers, when present, were generated afresh for each interval, and were interaurally uncorrelated.

All target and masker stimuli were scaled to have the same root mean square level, and presented at a nominal level of 60 dB sound pressure level. For HI listeners, however, additional individualized linear amplification was provided according to the NAL-RP prescription (Byrne *et al.*, 1991). A single set of gain values was calculated based on the average audiogram across the two ears and applied to each ear (i.e., the applied gain was symmetric). This accounted somewhat for any loss of sensitivity in this region (below 1500 Hz) while maintaining a comfortable loudness level.

2.3 Procedures

Stimuli were controlled in MATLAB (MathWorks Inc., Natick, MA) and presented via a 24-bit soundcard (RME HDSP 9632, Haimhausen, Germany) through a pair of headphones (Sennheiser HD280 Pro, Wedemark, Germany). The listener was seated in a double-walled sound-treated booth fitted with a computer monitor and mouse.

ITD sensitivity was measured using a detection task (as per Bernstein and Trahiotis, 2009). The four stimulus intervals were marked visually on the monitor, and the task of the listener was to indicate which of two intervals (the second or third) contained the dichotic target by clicking with the mouse on the corresponding interval marker. Feedback was provided. Thresholds were estimated using a 2-down 1-up adaptive procedure tracking 70.7% correct. The starting ITD was always 0.5 ms, and the step-size was a factor of 1.58 (until four reversals were recorded) and 1.12 thereafter. An upper limit of 1 ms was imposed on the ITD. A track terminated once 12 reversals were recorded, or after 80 trials, whichever came first. Thresholds were estimated for each subject in each condition by reconstructing psychometric functions from the adaptive tracks. This approach was used for two reasons. First, the approach has been shown to be less biased than the typical approach of averaging reversals (Thavam and Dietz, 2019). Second, there was a potential for phase ambiguities with the pure tone stimuli, especially for the higher frequencies at large ITD values, which could produce non-monotonicities in the psychometric function and lead to unstable adaptive tracks. To generate psychometric functions, all trials from all seven tracks were pooled and sorted according to ITD value. ITD values for which there were less than five trials in total were excluded. For the pure tone conditions, ITD values larger than half a period were also excluded, as the psychometric functions were not well behaved past that point. For the remaining ITD values, percent correct scores were calculated and a psychometric function generated. Logistic fits to the data were estimated using the psignifit toolbox version 2.5.6 for MATLAB (http://bootstrap-software.com/psignifit/about.php), and thresholds corresponding to 70.7% correct were extracted. In a number of cases, performance did not reach 70.7% within the half-period limit, and thresholds were considered to be "unmeasurable."

Before any testing, the listeners were given a brief familiarization routine to give them experience with the stimuli and task. During this routine, five examples of a particular stimulus were presented with an ITD of 0.5 ms. Listeners responded to each example and feedback was provided. This was repeated for each of the six kinds of stimuli (350 Hz tone, 750 Hz tone, 1150 Hz tone, speech, 750 Hz tone in noise, speech in noise). The familiarization routine also gave the experimenter an opportunity to confirm that the loudness of the stimuli (post-gain) was acceptable for the HI listeners. Following familiarization, each listener completed seven blocks of six adaptive tracks (one per condition). Within each block, the order of the six tracks was randomized. Familiarization and testing were completed during two visits of approximately 2 h each.

3. Results

Figure 1 shows individual threshold values for each of the stimulus conditions, with the data arranged in two columns according to the two listener groups. Symbols falling above the dotted line indicate listeners for whom a threshold could not be calculated. For cases in which all subjects in a group had a measurable threshold, the across-subject geometric mean is reported.

Focusing first on the quiet conditions (four leftmost pairs of columns), NH mean thresholds for the 350, 750, and 1150 Hz tones were 81, 58, and 84 μs, respectively, and were lowest for the speech stimulus (38 μs). Thresholds for the HI listeners varied widely, with some falling well within the normal range and others being unmeasurable. The poorest performance was observed for the higher pure tone frequencies, with one subject being unmeasurable at 750 Hz and seven of the nine being unmeasurable at 1150 Hz. On the other hand, thresholds were measurable for all HI subjects for the 350 Hz tones with a group mean of 130 μs. For the speech stimulus, thresholds were measurable for all HI subjects and the group mean was 94 μs.

To examine in more detail the individual variability in ITD sensitivity, the left column of Fig. 2 shows ITD thresholds for the three different tones as a function of audiometric thresholds at the corresponding pure tone frequencies.[2] These plots suggest that there is a relationship between ITD thresholds and hearing status, which becomes increasingly apparent as the frequency increases. Notably, for any given frequency, the subjects who had unmeasurable thresholds were consistently those with the poorest audiometric thresholds at that frequency. The right column of Fig. 2 again shows ITD thresholds for the three different tones, but in this case as a function of ITD thresholds for speech. It is clear from these plots that thresholds were consistently better for speech than for tones (the majority of points lie above the dashed line) and that the subjects with unmeasurable thresholds for tones did not have inordinate difficulties with the speech stimulus.

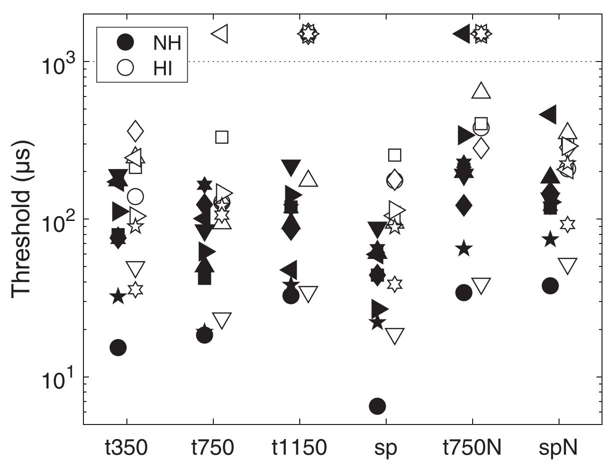

Fig. 1. ITD thresholds for each of the stimulus conditions. From the left are tones in quiet at 350, 750, and 1150 Hz ("t350," "t750," and "t1150") followed by speech in quiet ("sp"), 750-Hz tones in noise ("t750N"), and speech in noise ("spN"). The two columns of data per condition display thresholds for NH and HI listeners (filled and open symbols, respectively). Symbols above the dotted line at 1 ms indicate listeners for whom a threshold could not be calculated.

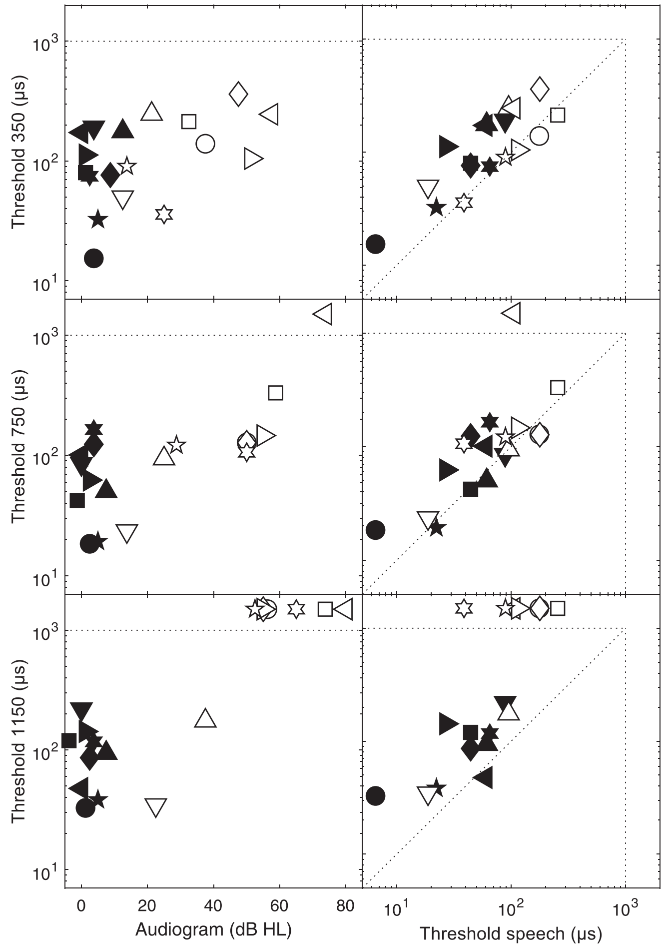

Fig. 2. Left column: ITD thresholds for each pure tone stimulus as a function of audiometric thresholds at that frequency. Right column: ITD thresholds for each pure tone stimulus as a function of ITD thresholds for speech. In all panels, individual listeners are indicated by different symbols (NH: filled; HI: open), and symbols beyond the dotted boundary at 1 ms indicate unmeasurable thresholds.

The two rightmost pairs of columns in Fig. 1 show threshold values for the two noise conditions. Again, symbols falling above the dotted line indicate listeners for whom a threshold could not be calculated. For the 750 Hz tone, the threshold for one NH and four HI listeners were unmeasurable in noise (including the HI listener for whom the threshold was unmeasurable in quiet). For the speech stimulus, thresholds were measurable for all listeners in noise. For NH listeners, the group mean threshold for speech increased from 38 to 127 μs in the presence of noise, while for HI listeners the group mean threshold increased from 94 to 196 μs. This represents about a threefold increase in both groups. Again, there was considerable overlap in thresholds between the two groups.

To examine the relationship between performance in quiet and in noise on an individual level, Fig. 3 shows ITD thresholds for the two noise conditions as a function of the corresponding quiet condition. For the pure tone stimulus (left panel) thresholds tended to be elevated in noise (most points lie above the diagonal), and four subjects with reasonable thresholds in quiet became unmeasurable in noise. For the speech stimulus (right panel), where thresholds were measured for all subjects, they were consistently elevated in the presence of noise (all points lie above the diagonal).

4. Discussion

For pure tone stimuli, we found that HI listeners generally had poorer ITD thresholds than NH listeners, but that there were large individual differences with thresholds spanning the range from normal to unmeasurable. These findings are quite consistent with the existing literature (e.g., Hawkins and Wightman, 1980; Buus *et al.*, 1984; Smoski and Trahiotis, 1986; Gabriel *et al.*, 1992; Lacher-Fougère and Demany, 2005; Spencer *et al.*, 2016).

The relationship we observed between ITD thresholds and audiometric thresholds raises the possibility that reduced stimulus audibility contributed to the observed

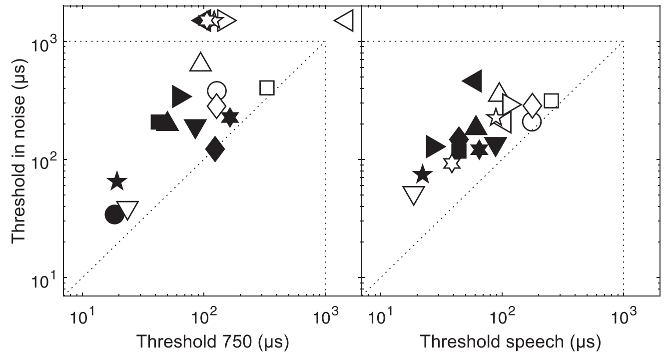

Fig. 3. ITD thresholds measured in noise as a function of the corresponding ITD thresholds measured in quiet, for 750 Hz tones (left panel) and speech (right panel). In both panels, individual listeners are indicated by different symbols (NH: filled; HI: open), and symbols beyond the dotted boundary at 1 ms indicate unmeasurable thresholds.

effects of hearing loss. In NH listeners, stimulus level does not have a significant effect on ITD thresholds within a moderate range (Thavam and Dietz, 2019) although thresholds can increase at the extremes (i.e., for very low or high sensation levels; Zwislocki and Feldman, 1956). Given that our stimuli were confined to the low-frequency region, where the losses for our HI listeners were generally not severe, the individualized amplification we provided should have accounted reasonably well for the loss of sensitivity. Thus, while sensation level cannot be ruled out, it does not seem adequate to explain the full effect of hearing loss on narrowband ITD thresholds. More likely, the observed relationship indicates that deficits in monaural peripheral encoding are translated into binaural coding deficits. Bernstein and Trahiotis (2016, 2018, 2019) have suggested that hearing loss, even if it is mild and restricted to high frequencies, is associated with increased internal noise that results in poorer binaural sensitivity across the spectrum.

The main new contribution of this study was the inclusion of a speech stimulus, which was intended to provide some data on how listeners perform with a complex broadband stimulus. We showed that thresholds were generally better for speech than for tones, in line with previous studies making this comparison in NH listeners (e.g., Hawkins *et al.*, 1978; Thavam and Dietz, 2019).[3] The primary goal of our experiment was to compare NH and HI listeners, and to test the specific hypothesis that the effects of hearing loss would be less pronounced for speech stimuli than for pure tone stimuli. The underlying idea was that increasing the bandwidth should provide redundant ITD information across frequency and diminish the impact of localized regions of neuronal loss. Our hypothesis was broadly supported, in that HI listeners all performed relatively well with the speech stimulus. In particular, those listeners for whom thresholds could not even be measured for 750 or 1150 Hz had no such difficulties for speech. However, our data also show that HI listeners performed relatively well for the 350 Hz tone, with all subjects having measurable thresholds, and many falling in the NH range. Thus it could be that the presence of low-frequency energy in the speech stimulus (rather than the increased bandwidth *per se*) was responsible for the improvement. Either way, the data suggest that with a broadband stimulus, ITD sensitivity is more robust than with a pure tone and more resistant to the effects of hearing loss.

This study also enabled us to compare the effect of noise on ITD thresholds in NH and HI listeners. We were interested to determine whether noise would exaggerate any group differences or perhaps reveal differences that are not apparent in quiet (e.g., Henry and Heinz, 2012). While ITD thresholds were generally elevated in the presence of noise (see also Stern *et al.*, 1983; Kolarik and Culling, 2009), we found no evidence that this elevation was larger in HI listeners than in NH listeners for speech or for tones (see also Strelcyk and Dau, 2009).

To conclude, our data suggest that the dramatic effects of hearing loss on ITD sensitivity that have repeatedly been observed with narrowband stimuli are less likely to be observed for a complex stimulus like speech. Thus, narrowband ITD thresholds may underestimate the ability of HI listeners to extract ITDs from everyday sounds. This stimulus dependence may be useful to consider in future attempts to understand the link between ITD sensitivity and the ability to benefit from spatial separation in "cocktail party" situations (e.g., Strelcyk and Dau, 2009; Neher *et al.*, 2011).

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References and links

[1]One listener's loss had a conductive component, but her PTA was calculated based on the sensorineural component only.

[2]Since our three frequencies did not correspond to standard audiometric frequencies, audiometric thresholds were estimated by averaging the two audiometric frequencies on either side (e.g., for 350 Hz the thresholds at 250 and 500 Hz were averaged).

[3]We note that thresholds for our NH listeners are somewhat higher than in previous studies using similar stimuli, which we attribute to a combination of experimental factors as described in detail by Thavam and Dietz (2019).

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